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ENGLISH LANGUAGE FACULTY OF ENGINEERING

RESEARCH PROJECT

MEng DEGREE

TITLE: Modeling of heat transfer between human body and clothing using thermophysiological model

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PREFACE

First of all, I would like to thank my family, especially my parents who made possible that I could spent a whole year studying abroad, and more especially to my grlfriend, who supported me in the difficult decision of leaving my home town.

With regards to the technical help and advices my gratitude goes to Iskra Simova and Delin Markov, my supervisors, and in general to all CERDECEN team leading Peter Stankov. Their help was very valuable and they always showed commitment whenever I needed any advice. I would also like to thank George Pichurov who also contributed explaining me some facts about the system and provided some useful data.

Also to my home university (UPNA), Technical University of Sofia, and more especially to Vlado Slavov who has helped us every time that we have had a problem, even out of the university.

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1.INTRODUCTION

1.1. IMPORTANCE OF THERMAL COMFORT

Thermal Discomfort, to paraphrase the classic definition of "thermal comfort" in Standard 55-66 of the American Society of Heating, Refrigerating and Air-Conditioning Engineers [2], is "that condition of the mind which expresses man's dissatisfaction with the thermal environment." The origin of this dissatisfaction may be psychological, physiological, or physical. Thermal Discomfort was originally associated by Houghten and Yaglou (1923) [11] with a sense of ‘`warmth" and "cold"; comfort was thus a neutral temperature sense. Winslow *et al. (1937) [9]* related unpleasant cold conditions to skin temperatures of sedentary subjects below 33.5-34^0 and unpleasant warm conditions to accumulation of sweat on skin surface (skin wettedness). Chattonet and Cabanac (1965) [4], showed that the judgment for thermal comfort was relative to the state of hyper- or hypothermia of the body, which they changed by use of water baths or exercise. Fanger (1967, 1970) [5, 6] demonstrated that the mean skin temperature, associated with comfort, decreased linearly with increasing activity (i.e., metabolic energy production) but that the regulatory sweating level associated with comfort increased linearly with activity. The sensory observations during the partitional calorimetric studies of Hardy and Stolwijk [10] in 1966, demonstrated (Gagge *et al.,* 1967) that any sudden thermal transient towards a comfortable environment caused an immediate sensation of comfort, although at the moment of the initial change the actual skin temperature and rate of sweating could be at levels not normally associated with comfort. Finally, Cabanac (1971) [3] showed that the magnitude of "pleasant" thermal stimuli depended on its "hedonic usefulness," which factor was determined by some internal body signal.

In industrialized countries, on average, people spend more than 90% of their time indoors. Such low fractions of time spent outdoors are typical for all industrialized countries, especially in seasons when thermal conditions are too hot or too cold for comfort. This means, in general, for indoor conditions, that indices based on steady state models are appropriate for thermal comfort assessments, while for the relative short times spent outdoors—mostly less than one hour—thermal steady state is hardly reached.

The thermal comfort term has to be clearly defined. In principal, there are three different approaches: a psychological, a thermophysiological and one based on the heat balance of the human body. The psychological definition, ``a condition of mind which expresses satisfaction with the thermal environment'' [14], certainly is very hard to deal with as due to its subjective character it reflects a wide inter-individual variation. Nevertheless, psychological aspects are important factors, especially outdoors. The thermophysiological definition of comfort is based on the firing of the thermal receptors in the skin and in the hypothalamus. Comfort in this sense is defined as the minimum rate of nervous signals from these receptors [15]. According to this energetic definition, the state of thermal comfort is reached when heat flows to and from the human body are balanced and skin temperature and sweat rate are within a comfort range, which depends only on metabolism [13]. Mean skin temperature plays a dominating role in both of the last two definitions.

Besides these three general definitions for thermal comfort there are many others specializing on warm or cold discomfort, e.g. the definition by Gagge [1]:

Thermal discomfort, defined as an expression of man's dissatisfaction with his thermal environment and measured by the magnitude estimates method, has been observed: (1) during humidity transients, when the ambient temperature is held constant at 32, 36, and 40°C; (2) during transients of the ambient temperature at constant relative humidity; and (3) during transients caused by both radiant heat and humidity while the ambient temperature is held at 32°C. The best single physiological index of thermal discomfort, especially without the presence of thermal radiation, is skin wettedness, which is defined as the ratio of the observed skin evaporative heat loss to the maximum evaporative capacity of the environment for a completely wet skin surface. Radiant heat (RH), by raising mean skin temperature by 1.5-2°C, causes the rate of rise of thermal discomfort with skin wettedness to increase. A biophysical effective temperature (ET), defined as the temperature of a black enclosure at 50% RH, in which man would exchange the same heat by radiation, convection, and evaporation as in the observed environment, correlates well with thermal discomfort regardless of the complexity of the thermal environment. The discomfort, caused by skin wittedness itself, may be attributed to the increasing strain caused first by the internal drive to secrete regulatory sweat, and second by the increased peripheral resistanc2 at the skin surface.

1.2 THERMO PSYCOLOGICAL HUMAN MODELS

Human's physiological functions and his capacity to function in a wide range of environmental conditions have been of interest to scientists and engineers for a long time. It is no wonder that the human thermoregulatory system, being a part of the whole mystery, has been the subject of many studies and, inevitably, many controversies as well. The controversies result, in part, because of the complexity of the human body and its functions, and the simplifications necessary to quantify them for formulating a successful mathematical model. The need or reason for developing such quantitative models comes from the necessity to simulate certain regulatory behaviors and their results to better understand the actual body actions or response.

The primary reasons for the complexity of the human thermoregulatory system are the number of variables involved and the feedback in the many control loops. The large number of quantitative models reflects the various approaches to study and understand this complex system.

Physiological and behavioral temperature regulation has been presented extensively in books and monographs by Hardy [25], Hardy, Gagge, and Stolwijk [26], Nangun [28], Bligh and Moore [19], and Bligh [18]. Mathematical models of the human thermal and/or thermoregulatory system have been reviewed by Fan, Hsu, and Hwang [21], Shitzer [30], Hardy [24], and Mitchell, Atkins, and Wyndham [27].

The different models can classify into:

1) One-Cylinder Models:
  a) Gagge model-two node (core and shell) model;
  b) Wyndham-Atkins model-multilayer model;
  c) Kawashima-Yamamoto model-three part model:
2) Multisegment Model:
  a) Stolwijk model.
3) Model with External Thermoregulation System-Webb model.

A simplified- negative-feedback human thermoregulatory system is in Fig. 2.1 [31]. The body heat capacitance can be subjected to a disturbance from environmental heat or cold or metabolic heat. The disturbance causes a change in the controlled variable (a body temperature or combination of temperatures). The controlled variable is measured by a transducer (thermal receptors) which generates related neural or hormonal information. This information, the feedback, is compared with reference information. The difference between the feedback and the reference, termed the error, is a measure of the effect of the disturbance on the controlled variable. The error activates a control center which provides a control action in such a way as to oppose the effect of the disturbance. In thermoregulation the control actions are means of modifying heat loss, heat production, or heat conservation by sweating, shivering, or vasomotor activity.

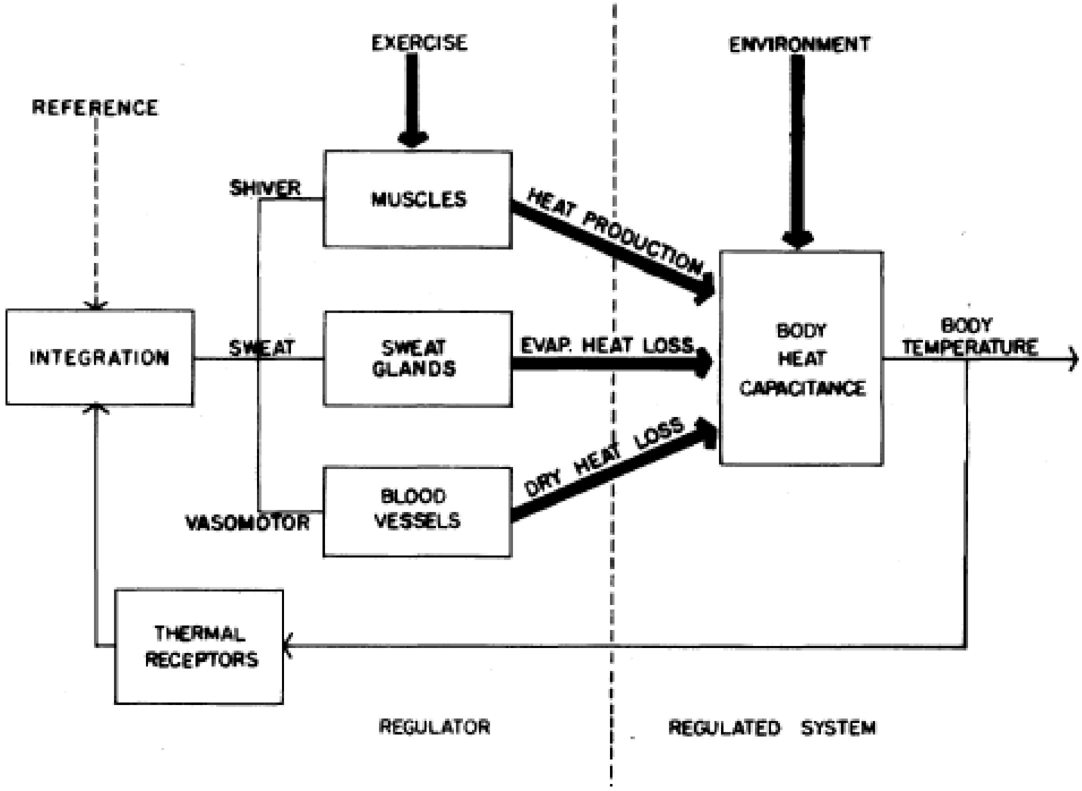

Fig 1. 1 Simplified block diagram of human thermoregulation

1.2.1 Gagge model basics

The Gagge model [22], written in Fortran, includes the most recent concepts of the regulation of body temperature during rest and exercise and during transient and steady states. A forerunner of the Gagge model was the one proposed by Gagge, Stolwijk, and Nishi [23]. Their model was developed to determine an environmental temperature scale, based onthe knowledge of the physiological heat regulation as it applies to comfort, temperature sensation, and health. The model considers the role of the temperature receptors in the hypothalamus to be accomplished primarily by the mean skin temperature and a central core temperature; the latter may be the rectal or the esophageal temperature.

In Gagge's simplified model, the human body is considered to be a single cylinder with two concentric layers; see Fig. 2.2. The inner layer is the central core and the outer layer is the skin shell.

Heat exchange between the human thermal system and the environment continuously takes place at the skin surface. Heat production continuously occurs inside the body by various biochemical actions or by exercise. Heat generated inside the body is transferred by convection to the skin surface through blood flow and by conduction in the radial direction. From the skin, heat is transferred to the environment by convection, conduction, radiation, and evaporation of sweat. Heat in excess of that which can be dissipated is stored in the tissue, resulting in a rise of body temperature.

There are seven independent environmental variables in the model: 1) metabolic rate, 2) work accomplished, 3) the combined heat transfer coefficient for radiation and convection, 4) the conductive heat transfer coefficient, 5) the insulation of clothing used, 6) the dry bulb temperature of the ambient air, and 7) the vapor pressure of the ambient air as measured by relative humidity, wet bulb temperature, or dew point temperature.
The principal physiological factors predicted by the model are mean skin temperature, core temperature, total evaporative heat loss, and skin blood flow.

1) The Controlled System: The classic heat balance equation can be written as [1]

$$S=M-W-E\pm R\pm C \qquad (1)$$

where

S = rate of heating (+) or cooling (-) of the body, W;
M= net rate of total metabolic heat production, W;
W = net rate of work accomplished, W;
E = rate of total evaporative heat loss, W;
R = rate of heat gained (+) or lost (-) by radiation, W;
C = rate of heat gained (+) or lost (-) by convection, W.

In a thermal equilibrium condition, S (or net rate of heat storage) is zero.
Metabolic rate M is proportional to the rate of oxygen (0_2) consumption, which may be measured directly. W = 0 for most tasks. For bicycle pedalling it is about 20%; that is, 80% of M stays in the body as heat and 20% of M becomes external work. The total evaporative heat loss E is divided into three parts: heat of vaporized moisture from the lungs during respiration, Eres; heat of vaporized water diffusing through the skin layer, Ediff; and heat of vaporized sweat necessary for the regulation of body temperature, Ersw. The sum, Eres + Ediff, is known as the insensible evaporative heat loss from the body while the component Ersw is the sensible loss.

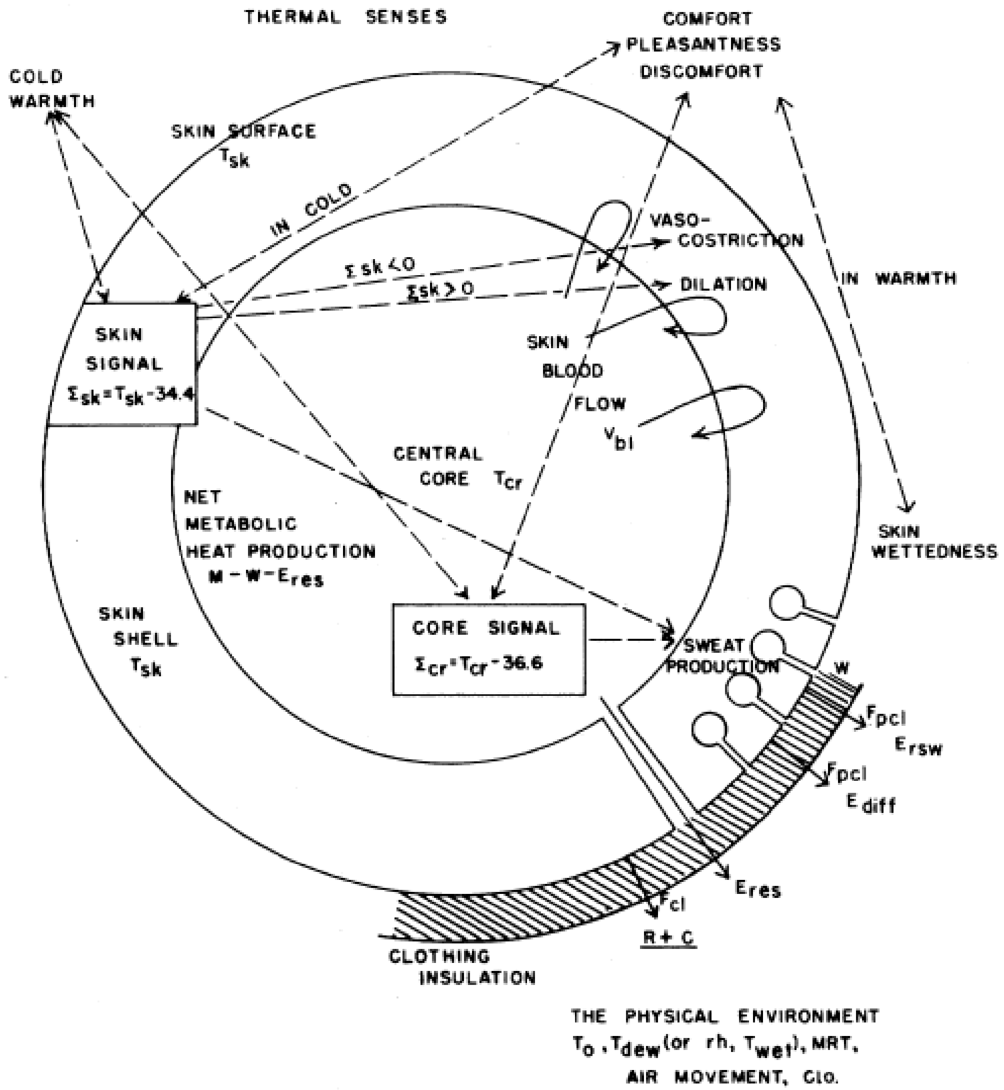

Fig 1. 2 A concentric shell model of man and his environment

The total rate of heat storage is

$$S = S_{sk} + S_{cr} \tag{2}$$

where

Ssk = rate of skin shell heat storage, W/m^2;
Scr = rate of core storage, W/m^2.

The net heat flow to and from the skin shell is given by

$$Ssk = Kmin\ (Tcr - Tsk) + Cbl\ VbI\ (Tcr - Tsk) - Esk - (R + C) \tag{3}$$

where

Kmin= minimum heat conductance of skin tissue, W/(m^2 .ºC);

Tcr= temperature of central core, ºC;

Tsk= temperature of skin shell, ºC;

Cbl= specific heat of blood, W(h)/(kg * °C);

Vbl= rate of skin blood flow, l/(h m^2);

Esk= evaporative heat loss from the skin surface, W/m^2 .

The net heat flow to and from the core is given by

Scr = (M- Eres - W) - Kmin (Tcr - Tsk) - Cbl Vbl (Tcr - Tsk). (4)

The rate of change in skin (shell) temperature, Tsk, and central core temperature, Tcr are given by

$\dot{T}$sk =Ssk *A/Csk (ºC/h) (5)

$\dot{T}$cr=Scr*A/Ccr (ºC/h) (6)

where

A = DuBois surface area, m^2;
CSk = total thermal capacity of the skin shell, W(h)/ºC;
Ccr = total thermal capacity of the core, W(h)/ºC;

In the above equations the cooling and warming is considered as Newtonian for the core and shell. The core and shell are assumed uniform at temperature Tcr and Tsk, respectively.
If the skin and core temperatures are at 34.1 ºC and 36.6 ºC, respectively, on initial exposure to an environment, then the values of Tsk and Tcr at any time are given by

$$Tsk = 34.1 + \int_0^t \dot{T}sk\, dt \quad (7)$$

$$Tcr = 34.1 + \int_0^t \dot{T}cr\, dt \quad (8)$$

2) The Controlling System: As mentioned above, the Gagge model assumes that the temperature signals from the skin shell and the central core are given by

$$\sum_{sk} = Tsk - 34.1 \quad (9)$$

$$\sum_{cr} = Tcr - 36.6. \quad (10)$$

The values 34.1 and 36.6 have been observed as the mean temperature of the skin and core when there is minimal regulatory effort in maintaining body temperature either by any vascular effort or by sweating. When these temperatures occur simultaneously during rest, the body is in a state of physiological thermal neutrality.

When $\sum_{sk}$ is negative, the skin senses "cold," and positive, "warmth." Likewise, when $\sum_{cr}$ is negative, the core senses "cold," and positive, "warmth." A "cold" signal from the skin primarily governs "vasoconstriction" in the vascular bed of the skin and thus reduces the blood flow from core to skin. A "warm" signal from the skin governs sweating. A warm signal from the core will cause dilation in the vascular bed and evoke sweating. The corresponding cold signal from the core will cause vasoconstriction but not as rapidly or effectively as one from the skin.

The skin blood flow, Vbl, at any time is given by

$$\dot{V}bl = (6.3 + 75 \sum_{cr})/(1 - O.5 \sum_{sk}), \quad l/(h * m^2). \quad (11)$$

This equation is based on a multicompartment model of Stolwijk and Hardy [32], who estimated for a cold $\sum_{sk}$ that, for each degree centimeter drop, skin blood flow will encounter a proportional increase in resistance. For the hands and feet alone, this resistance factor may be twice as great with each degree drop; for the head, vasoconstriction may be negligible. For the core, each degree centimeter rise will cause an increase in skin blood flow of 75 $l/(h*m^2)$ above a normal skin blood flow of 6.3 $l/(h*m^2)$, a value which occurs at rest during thermal neutrality. When $\sum_{cr}$ represents a cold signal, that is, Tcr < 36.6, and/or when $\sum_{sk}$ represents a warm signal, that is, Tsk > 34.1, the numerical value of $\sum$ in either case is considered as zero.

The rate of sweat production is written as

$$\dot{m}_{rsw} = 250 \sum_{cr} + 10(\sum_{cr}) (\sum_{sk}). \quad (12)$$

The regulatory sweating, m_{rsw}, in $g/(h \cdot m^2)$ at the skin surface, necessary for temperature regulation by evaporation, is activated both by the core signal $\sum_{cr}$ and by the product $(\sum_{sk})$ $(\sum_{cr})$ The first constant is from Saltin et al. [26], who observed that each degree change in core temperature above 36.6 ºC during exercise caused an average increase in sweating secretion of 250 $g/(h \cdot ºC^2 \cdot m^2)$. The second constant is from Stolwijk and Hardy [32], who have shown that the sweat drive during rest has the factor 100 g/(h ·ºC^2·m^2), representing the dual effect of a gain controller with an output described by the product ($\sum_{sk}$) ($\sum_{cr}$).

The heat loss from regulatory sweating is given by

$$Ersw = 0.7\ \dot{m}_{rsw}\ [2^{(Tsk\ 34.1)/3}] \qquad (13)$$

where 0.7 is the latent heat of sweat in W(h)/g. The 2-toa-power term is from Bullard et al. [20], who showed that skin temperature can modify locally the production of sweat. Stolwijk [31] later modified equation (13).

Gagge's two-node model is one of the simplest models in the current literature and its use is limited for exposure times shorter than an hour. However, it does include all of the important parameters, coefficients, and controls for man and his environment necessary to predict the quasi-equilibrium status for the whole body and the probable values of the three principal parameters related to the judgement of comfort and thermal sensation-skin and core temperature and skin wettedness.

2.OBJECTIVE AND LIMITATIONS

2.1. OBJECTIVE

In this thesis project, a complete analysis of the heat transfer between the human body and the surroundings in a indoor place is carried out so that more knowledge on this area is available and to give answers to different questions related to these matters. All the research, data and conclusions are intended to serve and suggest what is the best way to dress as a function of the activity that you are doing.

The estimation of the heat flux is totally connected with the kind of clothes you are wearing and the task you are executing. Thereby, an exhaustive study of the different kind of clothing and activities is to be carried out. This should server to estimate the heat transfer for different activities and clothing.

The work also distinguish between two situations, on one hand the place will be cooling by an air conditioning equipment and on the other hand, I'm going to simulate some cases in the same room without cooling with the aim of seeing which are the differences.

All the calculations of the study have been performed with a CFD (computer fluid dynamics) program called fluent 6.3 with which I've done the simulations. Also it has allowed me to calculate the temperature of the skin and the temperature of the clothes around all the profile of the human silhouette with the aim of seeing if the results in each case are realistic or not.

Finally the analysis of the theoretical air flux into the room is purpose of this work too.

2.2. LIMITATIONS

2.2.1 Physical boundaries and surronding conditions

This work is limited to study the heat transfer between the human body and the environment, as well as the flow and thermal characteristics inside the room and around the body. Therefore system physical boundaries are somehow well defined by the walls of the room and by the silhouette of the body, also the inlet and the outlet are clearly defined as a hole in the wall on the top (inlet) and on the bottom of the opposite wall (outlet).

As to the surroundings, the walls around the room are adiabatic for both heat and moisture, assuming that the placement of the room would be in the interior of a building.

In this work only the ambient temperature is used as parameter. Other factors such as humidity in the air, velocity, etc. will also have influence especially in the convective heat transfer coefficient. Solar radiation will also affect the heat transfer through the walls. Finally the heat conduction though the air is very sensitive to its composition, humidity, etc. which can change with time. However, taking into account all those variables is unfeasible so constant values are imposed and only ambient temperature is changed

2.2.2. Limitations of other nature

There are many other limitations aside from the physical boundaries of the study system. Among others, knowledge of the real physical process and tools to tackle it, time and technical-economical resources can be included in this group.

The complexity of natural convection type flows is high and although the basis is well understood there are many details (which can determine some problems) that are difficult to predict. Turbulent flow is an additional difficulty. These facts make difficult to produce a precise mathematical model which is necessary to use and after solved so that some questions can be answered. Therefore, this is a very important limit that must always be bear in mind.

Regarding with the time, this project is not limited a priori. However, in practical terms, a highly detail modeling and precise study of the system with all the variables involved would make this project (broadly speaking anyone) too long. It is a task of the author of any scientific-engineering problem to set this limits and weigh up the benefits of increasing the level of detail, and wonder if they really are necessary for the goals of the work. It is always possible, however, to suggest future work lines so that more people can continue and further investigate the case.

Finally, and to some extent connected with time limit, there are the technical-economical resources. For this particular case, due to technical, economical and time reasons, it is not feasible to carry out any direct experiment. That is why all this work is only theoretical, an important fact to bear in mind, which will make difficult to validate and judge the results of this work. This is a common practice in engineering, and should anyhow be helpful when it comes to make decisions about this or similar systems.

2.3. SELECTION OF THE CASES

In the beginning of the simulation process we needed to take a decision about the characteristics of the cases and the initial conditions. We've tried to cover different situations that we can find as a function of the clothing ensembles and the activity of a person.

For the cases with cooling this is the selection:

On one hand, for the activities we chose five different activity levels:

- Sedentary activity: 1.2 met
- Teaching, lab work: 1.6 met
- Medium activity: 2 met
- Ironing: 3 met
- Aerobic, dancing: 6 met

On the other hand, for the clothing we focused in five different ensembles:

- Walking shorts, short-sleeve shirt: 0.37 clo
- Trousers, long-sleeve shirt: 0.60 clo
- Trousers, long-sleeve shirt and suit jacket: 0.93 clo
- Trousers, long-sleeve shirt, long-sleeve sweater, t-shirt, suit jacket and long underwear bottoms: 1.3 clo
- Combination of the second and the third ensemble: 1.53 clo

The fourth ensemble can be seen like a combination of the first and the third ensemble. We studied the last two ensembles because we wanted to compare the different cases and if the sum of the clothing affects or has any relation with the heat transfer.

All this values are coming from the ASHRAE handbook

For the cases without cooling we studied three different activities which are: sedentary activity, medium activity and ironing.

Otherwise, for the clothes we chose three levels of clothing:

- Walking shorts, short-sleeve shirt: 0.37 clo
- Trousers, long-sleeve shirt and suit jacket: 0.93 clo
- Trousers, long-sleeve shirt, long-sleeve sweater, t-shirt, suit jacket and long underwear bottoms: 1.3 clo

The reason to select only three activities is because we consider that is enough in order to compare and to see if there is any similitude with the same cases in the cooling situation. Also we can analyze if the sum of clothing has any similitude with the case of 1.3 clo.

This is the table which summarizes all the cases with the corresponding value of clothing and activity:

Cases	Regime	Clothing m^2K/W	Clo	Activity W/m2	Met
1.		0.057		70	1,2 (sedentary activity)
2.	Summer,	0.057		93	1,6 (teaching, lab. work)
3.	cooling	0.057	0.37	116	2,0 (medium activity)
4.	t=22^{o}C	0.057		174	3,0 (ironing)
5.		0.057		348	6.0 (aerobic, dancing)
6.	Summer,	0.093		70	1,2 (sedentary activity)
7.	cooling	0.093	0.60	116	2,0 (medium activity)
8.	t=22^{o}C	0.093		174	3,0 (ironing)
9.		0.144		70	1,2 (sedentary activity)
10.	Summer,	0.144		93	1,6 (teaching, lab. work)
11.	cooling	0.144	0.93	116	2,0 (medium activity)
12.	t=22^{o}C	0.144		174	3,0 (ironing)
13.		0.144		348	6.0 (aerobic, dancing)
14.		0,2		70	1,2 (sedentary activity)
15.	Summer,	0,2		93	1,6 (teaching, lab. work)
16.	cooling	0,2	1.3	116	2,0 (medium activity)
17.	t=22^{o}C	0,2		174	3,0 (ironing)
18.		0,2		348	6.0 (aerobic, dancing)
19.	Summer,	0,237		70	1,2 (sedentary activity)
20.	cooling	0,237	1.53	116	2,0 (medium activity)
21.	t=22^{o}C	0,237		174	3,0 (ironing)

22.	Summer, no	0.057		70	1,2 (sedentary activity)
23.	cooling	0.057	0.37	116	2,0 (medium activity)
24.	t=28^{o}C	0.057		174	3,0 (ironing)
25.	Summer, no	0.144		70	1,2 (sedentary activity)
26.	cooling	0.144	0.93	116	2,0 (medium activity)
27.	t=28^{o}C	0.144		174	3,0 (ironing)
28.	Summer, no	0,2		70	1,2 (sedentary activity)
29.	cooling	0,2	1.3	116	2,0 (medium activity)
30.	t=28^{o}C	0,2		174	3,0 (ironing)

3.THEORY AND METHODS

3.1. METHOD

3.1.1 Introduction

This work has been carried out following a top-down approach. First off all, boundaries are studied, specified and its parameters are calculated. Also, properties and specifications of the working fluids are obtained and modeled accordingly. Once all the components (i.e. boundaries and fluids) of the system are clearly defined, theories are applied to work out the results.

In this way, boundaries of the system are decomposed into smaller units: sidewalls, human body, inlet and outlet. In the next level, each part is again composed by smaller units according to its construction specifications. Once the smallest units are specified their properties and specifications related to heat transfer mechanisms are found. In order to build up each boundary's model, formulations of different complexity are used depending on the construction type, geometry and materials involved in it.

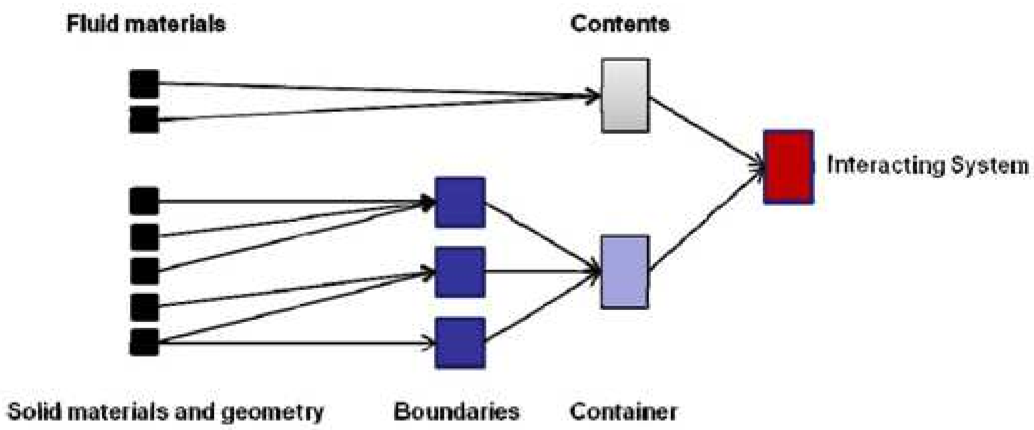

Fig 3. 1 Composition of the study system

The present project can be considered completely theoretical in the sense that no experimental measure is carried out to compare and validate results obtained after the application of different theories and methods. Data from experiments previously carried out are taken as input for different calculations (i.e. material properties and empirical expression), but not explicit measurement is carried out.

Several software packages were used in different parts of the work to calculate in an automated way precise calculations and to carry out finite and volume element based simulations; among others: Fluent, Gambit, Microsoft visual C++ and Wolfram Mathematica. Computational fluid dynamics and heat transfer simulations were run on a double 3 GHz processor and 4 GB RAM memory servers and Pentium R 3 GHz with 2 GB of RAM memory computers.

Various type sources of information were necessary in this work. Information about the general case, components of the human body model and other factors related with the boundary conditions was obtained by means of George Pichurov's thesis. Major properties and specifications about the values of the clothing and the activity were taken from ASHRAE handbook and others were consulted in different reference sources cited in the work. Aside from these other references were used to contrast information used throughout the project.

3.1.2. CFD solver

3.1.2.1 Steps of the process

To make de CFD simulations I have used the program called Fluent 6.3 which is one of the most important commercially codes due to thousands of companies throughout the world use it. The Fluent package includes the following parts:

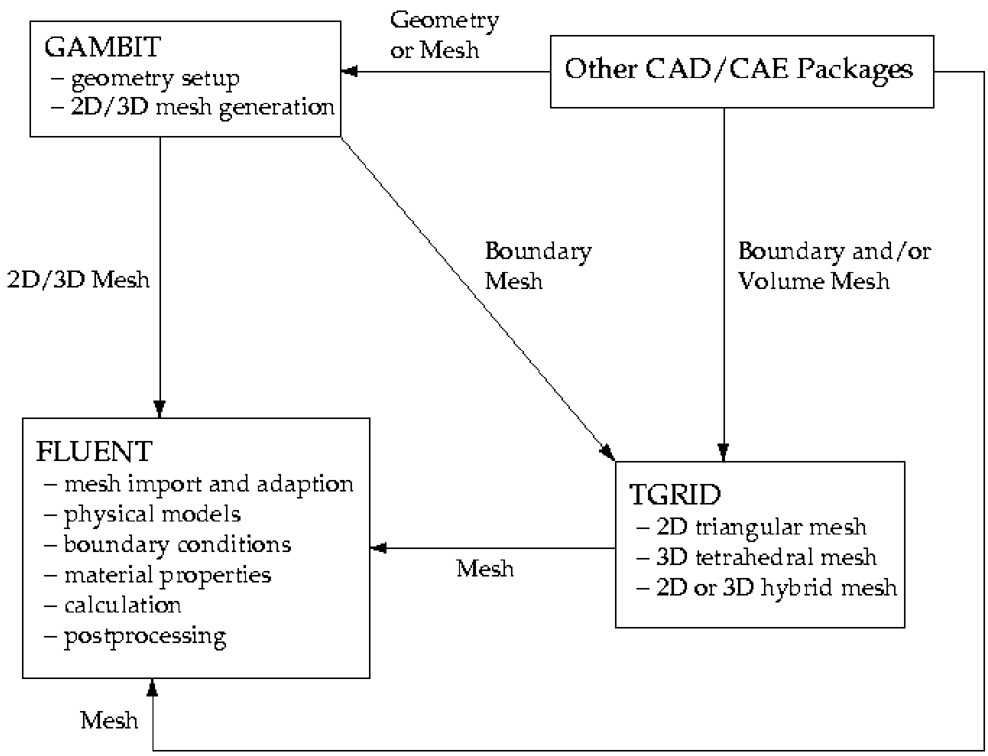

Fig 3. 2 Basic program structure

FLUENT is the solver

GAMBIT is the preprocessor for geometry modeling and mesh generation

TGrid is an additional preprocessor that can generate volume meshes from existing boundary meshes

Filters (translators) for import of surface and volume meshes from CAD/CAE packages such as ANSYS, CGNS, I-deas, NASTRAN, PATRAN, and others.

The resolution of a CFD problem has different steps:
1-Pre-processing:
Include the CAD design, the mesh creation. The CAD design can be created with Gambit or imported from another compatible CAD package

The creation of the mesh is the most important step in CFD. The mesh density, or inversely, the size of the control volumes, determines the accuracy of the simulation.
The mesh consists of four major concepts, volumes, surfaces, edges and nodes. These concepts are hierarchical, a volume is bounded by surfaces, a surface is bounded by edges and an edge consists of nodes.

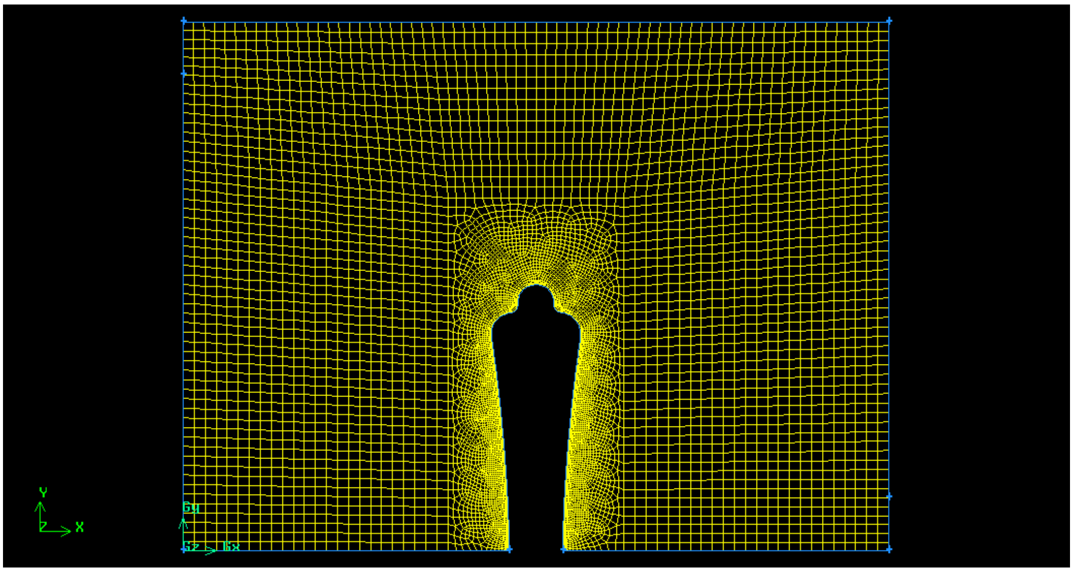

Fig 3.3 General view of the room mesh

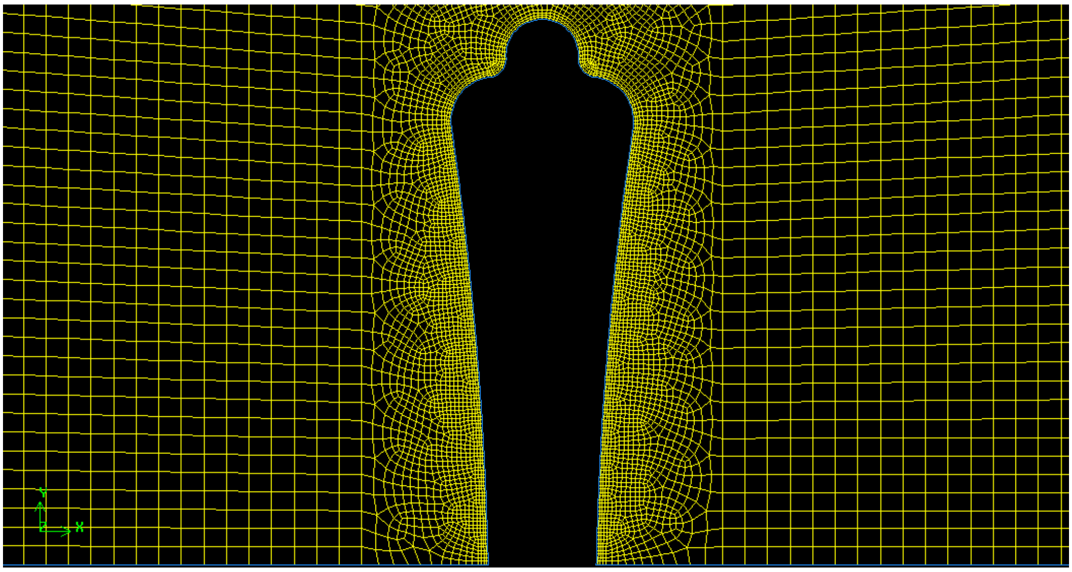

Fig 3.4 Mesh around the body

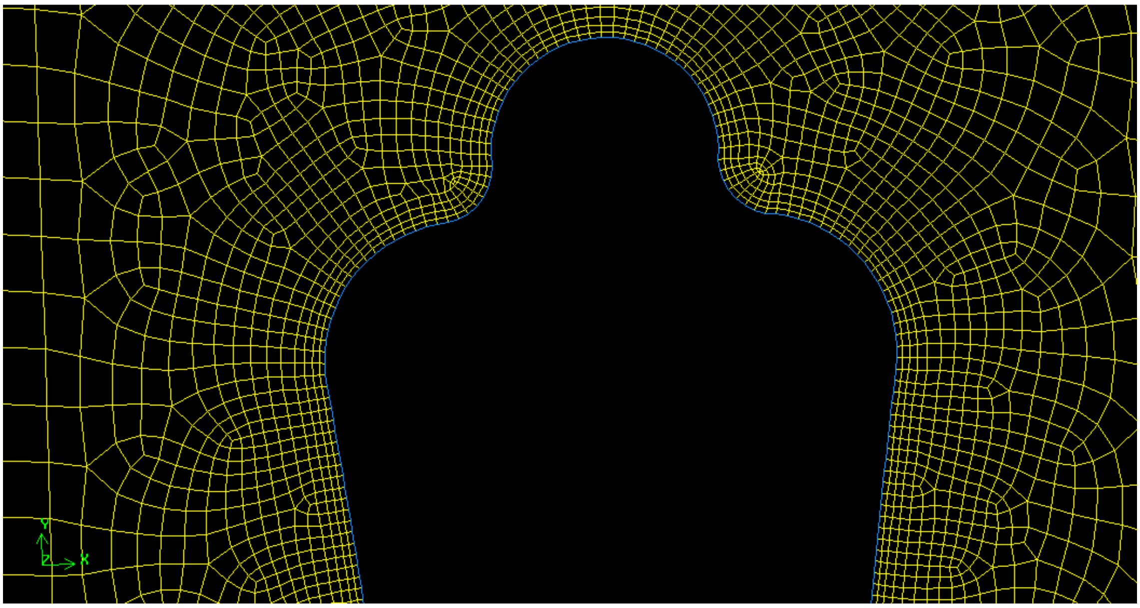

Fig 3.5 Detail of the mesh

2-Solver:

At this point the completed geometry can be imported into the solver and the CFD simulation is started. Once a grid has been read into Fluent, all remaining operations are performed within the solver. These include setting boundary conditions, defining fluid properties, executing the solution, refining the grid, and viewing and postprocessing the results.

3-Post-processing:

When the simulation has converged the last data set is stored as a final solution. This data set has a record of the status of all elements in the model, temperature, densities, pressures, flow aspects etc. To be able to interpret the data it needs to be ordered and reduced to comprehensible sizes. This displaying of the data is called post-processing

and makes it possible to compare the different simulations with each other and with external data.
There are as many ways of displaying the data as there are data points so it is important to select the data representation that is required for the desired data comparison. Some of the standard visualization options available are contour plots and velocity vector plots.
Contour plots will give a plot in a defined collection of control volumes, which can be a plane or a volume. Other variables that can be used for contour plots are temperature, magnitude of velocity components, turbulence components, local pressure etc.
Velocity vector plots can be made to get an insight into the flow patterns in the overall geometry or detailed at specific locations. The density and magnification of the velocity vectors in the specified field can be manually changed to get a most optimal picture.

Besides these qualitative data export methods it is also possible to export the numerical data in many different forms. Direct export of selected data sets is facilitated for a number of external applications; also it is possible to export data in ASCII format for further manipulation.

Another method for exporting the numerical data is the two-dimensional plot function in which two data sets can be plotted against each other. This function is useful when for example radial velocity or temperature profiles need to be compared. From different simulations identical plots can be created and a direct comparison of the numerical data is possible.

3.1.2.2 Solver

For the development of the simulations presented in this work the CFD solver was Fluent 5.x/6.x, a finite volumes solver provided by Fluent Inc.
Fluent 5.x/6.x is a Navier-Stokes based CFD principles.
Table 3.1 shows a analysis of the main features of this CFD code, showing their technical and mathematical characteristics, and the applicability for solving different kinds of physical problems:

Feature	Fluent 5.x/6.x
Numerical method	Finite Volumes
Orientation	Fluid-dynamics equations solver
PRE-PROCESSING	
Feature program	Gambit 2.x
Mesh type	Structured/Unstructured mesh
Mesh capability	Excellent for 2D and 3D
Geometry design	CAD oriented. Suitable for complex geometries
User interface	Easy to use if familiarized with CAD software
Mesh optimization	Features for mesh local improvement/optimization
SOLVER	
Continuity condition	Based on density and velocity gradients
Solver type	Segregated/Coupled
Parametric studies	No
Adaptive mesh features	Yes
Smoothing mesh features	Yes
User interface	Command-based Complex if not used to it
Problem set-up difficulty	Complex if not used to the interface
Applicability	Fluid dynamics problems with heat/mass transfer
Turbulence modelling	Excellent for 2D and 3D
Complementary models	Heat/mass transfer Buoyancy models Chemical reaction models Porous media flow
POST-PROCESSING	
Graphical resolution	Excellent
Data export features	Text files XY plots Variable contours

Table 3.1

3.2. THEORY

3.2.1. Fluid dynamics and heat transfer basics

3.2.1.1. Introduction

Several theories are applied on this work. Calculations of heat losses imply governing equations for the three heat transfer mechanisms: conduction, convection and radiation. Conduction in solid materials is calculated in some occasion by means of thermal resistances. Those are expressions derived from steady state solutions of general conduction equation for some common geometries. Basic models make use of basic mass and energy conservation equations. Finally, the set of equations solved in CFD software packages are based on the differential form of fluid dynamics equations of motion and turbulence models.

First governing equations for the fluid motion will be presented, including the equation of energy. Fluid formulation of energy equation is then particularized for a solid case. Convection is a heat transfer mechanism that involves heat transfer from a fluid to a solid or vice versa, thereby it is based in the former equations. Radiation equations are not presented here since due to some simplifications made they are not directly used in this work. Finally equations are averaged to show the statistical description of turbulence and k-ε model is presented. Turbulence relations for boundary conditions are also discussed.

3.2.1.2. Governing equations of fluid dynamics

In the continuum formulation, generally speaking, there are six[1] variables that define completely the state of the fluid at any point of the domain: u_x, u_y, u_z, p, ρ and T. Therefore six equations are necessary to solve these variables (are function of time and space): equations of continuity (1), momentum (3), energy (1) and state (1). The equation of state can be very complex and usually simple equations (e.g. simple perfect gas) or simplifications (e.g. incompressible fluid, incompressible flow, linear dependence of density on temperature) are used instead. Next general equations of continuity, momentum and energy are shown[2]

Continuity,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \qquad (3.1)$$

Momentum equations, derived from Newton's second law of motion,

$$\frac{D(\rho u)}{Dt} = \frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u u) = \rho f + \nabla \cdot \bar{\bar{\sigma}} \qquad (3.2)$$

where f (vector) and σ (stress tensor) are body and surface forces per unit of volume. The constitutive model for a fluid relates the components of the stress tensor with the variables of the velocity field (ux, uy, uz). The liquid involved in this project is the air which is a newtonian fluid.

[1]In other cases there might be further scalar variables involved, but not for the cases solved in this work

[2] Note that vectors are represented by bold characters, and tensors have double upper dash. Nabla operator for cartesian coordinates is $\nabla = \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}\right)^T$ and $\bar{\bar{I}}$ is the unit tensor. Expressions have taken from [33], [34] and [35].

Therefore, only the result after the application of the constitutive model for a Newtonian fluid is presented, i.e., the so called Navier-Stokes equations (note that there is one scalar equation for each spatial component):

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u u) = \rho f - \nabla p + \nabla \cdot (\bar{\bar{\tau}}) \qquad (3.3)$$

with

$$\bar{\bar{\tau}} = \mu \left[(\nabla u + \nabla u^T) - \frac{2}{3} \nabla \cdot u \bar{\bar{I}} \right]$$

Energy

$$\frac{\partial(\rho e)}{\partial t} + \nabla[u(\rho e + p)] = \nabla(\lambda \nabla T) + \nabla \cdot (\bar{\bar{\tau}} \cdot u) + e_s \qquad (3.4)$$

where

$$e = h - \frac{p}{\rho} + \frac{u^2}{2}$$

Note that h is here the specific enthalpy and not the convective heat transfer coefficient that is represented by h for the rest of this work. e is the energy per unit of mass (J kg^{-1}) and e_s are volumetric energy source (J s^{-1} m^{-3}).

3.2.1.3. General heat conduction equation

Taking the energy equation presented before, considering ***u*** = 0 and applying some thermodynamic relations a general equation for conduction can be obtained [1]:

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + e_s \qquad (3.5)$$

where C is the specific heat capacity of a solid (J kg^{-1} k^{-1}).

3.2.1.4. Turbulence basic equations and overview of k-ε model

Defining turbulence is not easy and there is not any complete and formal definition. However, the turbulence can be described as a "state of continuous instability" [5]. This continuous instability makes very difficult to accurately predict the flow, thereby normally it is statistically described in terms of average quantities. In this manner, in the Reynolds-average approach variable fields are divided into mean ($\widehat{\phi}$) and fluctuating (ϕ') components:

$$u = \hat{u} + u'$$

$$p = \hat{p} + p'$$

$$T = \hat{T} + T'$$

...

After introducing these expressions into the governing equations and performing time average on them, the so called Reynolds averaged Navier-Stokes (RANS) equations are obtained[3]:

$$\frac{\partial \hat{\rho}}{\partial t} + \frac{\partial (\hat{\rho}\, \widehat{u_i})}{\partial x_i} = 0 \qquad (3.6)$$

$$\frac{\partial(\hat{\rho}\hat{u}_i)}{\partial t} + \frac{\partial(\hat{\rho}\hat{u}_i\hat{u}_j)}{\partial x_j} = \hat{\rho} f_i - \frac{\partial \hat{p}}{\partial x_i} + \frac{\partial\left[\mu\left(\frac{\partial \hat{u}_i}{\partial x_j} + \frac{\partial \hat{u}_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial \hat{u}_l}{\partial x_l}\right)\right]}{\partial x_j} + \frac{\partial\left(-\hat{\rho}\overline{u_i' u_j'}\right)}{\partial x_j} \qquad (3.7)$$

However, now new unknowns are present: $-\hat{\rho}\overline{u_i' u_j'}$ named Reynolds stresses. The tensor $\overline{u_i' u_j'}$ is diagonally symmetrical so six new unknowns are to be solved a priori. Thus new equations need to be introduced to the system. However, various turbulence models make use of the Boussinesq hypothesis:

$$-\hat{\rho}\overline{u_i' u_j'} = \mu_t\left(\frac{\partial \widehat{u_i}}{\partial x_j} + \frac{\partial \widehat{u_j}}{\partial x_i}\right) - \frac{2}{3}\left(\hat{\rho} k + \mu_t \frac{\partial \widehat{u_k}}{\partial x_k}\right)\delta_{ij} \qquad (3.8)$$

Models (k-ε one used in this work among them) that use this hypothesis need to solve only one or two additional equations to calculate the turbulent viscosity scalar, making it computationally attractive.

k-ε models

These turbulence models are perhaps the most common one used due to their robustness and reasonable good accuracy. Nowadays three different models are used: standard k-ε, RNG k-ε and Realizable k-ε models respectively.

These models are grounded on the transport equations[4] for turbulence kinetic energy (k) and turbulent dissipation rate (ε). In the case of the standard model, the two equations are:

[3]Cartesian tensor notation is usually use to present turbulence related equations for simplicity reasons. Energy equation is specifically presented next for k-ε turbulent model.

$$\frac{\partial(\hat{\rho}k)}{\partial t}+\frac{\partial(\hat{\rho}k\widehat{u_i})}{\partial x_i}=\frac{\partial\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]}{\partial x_j}+G_k+G_b-\hat{\rho}\epsilon-Y_M+S_k \qquad (3.9)$$

$$\frac{\partial(\hat{\rho}\epsilon)}{\partial t}+\frac{\partial(\hat{\rho}\epsilon\widehat{u_i})}{\partial x_i}=\frac{\partial\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right]}{\partial x_j}+C_{1\varepsilon}\frac{\epsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\hat{\rho}\frac{\epsilon^2}{k}+S_\varepsilon \qquad (3.10)$$

with:

G_k Generation of turbulence kinetic energy due to mean velocity gradients

G_b Generation of turbulence kinetic energy due to buoyancy.

Y_M Contribution of the fluctuating dilatation in compressible turbulence to the overall

σ_k Turbulent Prandtl number for k.

σ_ε Turbulent Prandtl number for ε.

S_k Additional source terms for k.

S_ε Additional source terms for ε

The optimized constants for the majority of the flows are: C1ε=1.44, C2ε=1.92, Cμ=0.09, σk=1, σε=1.3.

After the resolution of k and ε variables the turbulent viscosity is calculated and used in the Boussinesq hypothesis.

$$\mu_t=\hat{\rho}C_\mu\frac{k^2}{\varepsilon} \qquad (3.11)$$

C_μ is constant for the standard k-ε model. In the case of RNG k-ε model a differential relation can be used. For the realizable k-ε model it is not constant and depends on other parameters involved in the transport equations.

The energy equation for average variables in the k-ε model is:

$$\frac{\partial(\hat{\rho}\hat{e})}{\partial t}+\frac{\partial[\widehat{u_i}(\hat{\rho}\hat{e}+\hat{p})]}{\partial x_i}=\frac{\partial\left[\lambda_{eff}\frac{\partial\hat{T}}{\partial x_j}+\widehat{u_i}\tau_{if_{eff}}\right]}{\partial x}+e_s \qquad (3.12)$$

[4]Here only transport equations for the standard model are presented. For further understanding of these equations and the difference with other models see [33], [35] or other related literature.

with

$$\tau_{ij_{eff}} = u_{eff}\left(\frac{\partial \hat{u_i}}{\partial x_j} + \frac{\partial \hat{u_j}}{\partial x_i}\right) - \frac{2}{3}\mu_{eff}\frac{\partial \widehat{u_k}}{\partial \widehat{x_k}}\delta_{ij}$$

And in the case of standard and realizable models,

$$\lambda_{eff} = \lambda + \frac{C_p \mu_t}{Pr_t}$$

Turbulent boundary relations

When it comes to k and ε turbulent parameters at inlet type boundary conditions, it is important they represent in the best possible way turbulent properties in these zones. When there is no empirical measurement that provides this data (as it is in this work), some empirical relations for duct flows are useful to make a reasonable good guess about these variables.

Turbulent intensity can be defined[5] at inlet boundaries as:

$$I = \frac{\sqrt{\frac{1}{3}\left(\overline{u_x^{\prime 2}} + \overline{u_y^{\prime 2}} + \overline{u_z^{\prime 2}}\right)}}{U_{avg}} = 0.16(Re_D)^{-\frac{1}{8}} \tag{3.13}$$

And

$$Re_D = \frac{U_{avg} d_i}{v} \tag{3.14}$$

where $U_{avg}$is the average velocity at the inlet: $U_{avg} = \dot{V}/A_c$

Kinetic turbulent energy is defined as:

$$k = \frac{1}{2}\left(\overline{u_x^{\prime 2}} + \overline{u_y^{\prime 2}} + \overline{u_z^{\prime 2}}\right) \tag{3.15}$$

Therefore, combining expressions (3.13), (3.14) and (3.15), it is got:

$$k = \frac{3}{2}\left[0.16\left(\frac{U_{avg} d_i}{v}\right)^{-\frac{1}{8}} U_{avg}\right]^2 = \frac{3}{2}\left[0.16\left(\frac{d_i}{v}\right)^{-\frac{1}{8}} U_{avg}{}^{7/8}\right]^2 \tag{3.16}$$

Finally, to calculate ε, next expression is used,

$$\epsilon = C_\mu^{3/4}\frac{k^{3/2}}{0.07 d_i} \tag{3.17}$$

[5]Most of the expressions are taken from [35].

3.2.2. Computational Fluid Dynamics (CFD) basics

3.2.2.1. Introduction

Analytical solution of the set of partial differential equations of fluid dynamics and turbulence described earlier is known for very few simple cases and geometries. These equations are non-linear and they are coupled one to the other. That is why the approach is usually to find an approximate solution to these equations numerically via the so called Computational Fluid Dynamics discipline.

Generally the main advantages of the CFD approach in comparison with direct experimental one can be summed up as:

- Lower cost
- Faster achievement of the solution
- Information of variables at any point of the domain

However, solution for some problems is not possible to achieve. The speed of finding a solution is also a moot point in some cases. Usually this happens due to strong non linearities, complex geometries, etc. that lead to very complex flow simulations.
Aside from these, there are other disadvantages and limitations of CFD such as:

- Based on a mathematical model that could not represent precisely the real physical process.
- Based on numerical methods that might produce incorrect results in some cases.
- Hard to judge and assure if the solution obtained really corresponds with the reality.

Computational fluid dynamics is based like every numerical method on the discretization of the real domain, boundaries and time (when applicable). In other words, the continuous variables of space and time are replaced by discrete variables:

$$f(x, y, z, t)\ in\ \Omega, \partial\Omega\ and\ t_i < t < t_f \rightarrow$$

$$f_{ij}\left(x_i y_i z_i t_j\right)\ for\ i = 1,2 \ldots N\ and\ j = 1,2 \ldots N$$

The process of solving the system of partial non-linear coupled differential equations for continuous variables is replaced by the solving an algebraic system of equations for discrete variables. This, roughly speaking consists of inverting a matrix that usually requires performing many iterations by the computer. Once the solution is found for every point of the grid and time, the solution is interpolated for any other point of the domain (Ω) and time (t).

3.2.2.2. Brief description of discretization methods and computational grids

There are plenty of methods to discretize the space and time. When it comes to the space, the most common ones are finite difference method, finite element method and finite volume method. The last two are the methods that are usually implemented in both CFD and other FEA (Finite Element Analysis) software packages. In Fluent cases finite volume method is used. Comsol Multiphysics, however, uses the finite element method. Both methods are popular and generally speaking better suited to discretize complex geometries than finite difference method is.

The finite difference method is based on the differential form of the governing equations, and uses Taylor series to approximate the derivatives of the variables. The finite volume method, however, is based on the integral form and the space discretization is directly done in the physical domain. Its flexibility makes this method very attractive to implement in CFD based softwares. Finally, the finite element method uses a weak form of the integral from of the governing equations. It decomposes the problem into elements and an approximate solution is created for each element, later all the components are put together to obtain a global solution.

Regarding to the temporal discretization several schemes are possible. However, the fundamental methods to discretize the time are the explicit (forward) or implicit (backward) methods. The former is easier to implement but the maximum time step is limited to avoid stability problems, and it depends on the grid elements sizes and other parameters of the problem. Implicit method is trickier to implement and require the variables to be solved simultaneously in each time step.

Regarding the computational grid, it can be classified in two large groups: structured and unstructured grids. The formers can be identified with the use of indexes as they are ordered according to the boundaries. The cells are made of quadrilateral elements in 2D and hexahedra in 3D. The latter ones can not be identified by any index because they do not follow any type of particular order. For 2D only triangle cells or combined with quadrilaterals cells are used whereas for 3D a mix of tetrahedral, hexahedral, pyramids and prisms are used.

3.2.2.3. Under relaxation factors

Under relaxation factor are used in computational fluid dynamics to “relax” the solution after each iteration. This means that the solution of the variables in each iteration is not the one calculated (new solution) with the program algorithm but a mix between the old and the new one:

$$\Phi_{i+1} = \Phi_i + b\Delta\Phi \qquad (3.18)$$

In the previous expression *b* is the under relaxation factor which can go from 0 to 1. This technique permits to control the stability of the solution so that it does not diverge due to the non linearity nature of the underlying equations. In particular turbulent and natural convection flows are highly unstable and as [9] recommends they should be lowered. These low factors lead to an extreme increase in computational time to find the solution to the problems.

3.2.2.4. Convergence criterion

There is not any universal way to judge if a solution has converged. Usually scaled residuals are used to judge convergence in Fluent, being 10-3 for all variables except 10-6 for energy the default criterion. However if a good initial guess is given these residuals may not drop. There are other cases as well where residuals may be misleading. However, a converged solution should always have stable residuals. Other common way of judging convergence is to monitor global variables or fluxes, or local variables and wait until they reach stable values. For instance checking mass or heat balance are good approaches as to judging convergence (in each time step for transient simulations and in throughout the global iterative process for the steady state cases). Also stabilization of residuals and global heat balance was accounted for.

3.3. GENERAL APPROXIMATIONS, ASSUMPTIONS AND SIMPLIFICATIONS

3.3.1. Introduction

The relevance of approximations, simplifications or assumptions made in every work must always be carefully explained and discussed. In fact, every engineering and scientific work is based on theories, methods, etc. where hypothesis and assumptions are constantly made. However, if any result is due to be precise enough, these assumptions should be correct and based on previous results, empirical observation or other theories that justify these decisions. Some minor assumptions made in this work are explained throughout this text. However, here, main assumptions made as to the physical model of the fluid and flow inside the room is discussed. These assumptions are:

- No inclusion of the viscous dissipation term in the energy equation.
- Use of Boussinesq approximation to model buoyancy driven flow.

3.3.2. On the viscous dissipation term

Viscous dissipation term in the energy equation,

$$\nabla \cdot \left\{ \mu \left[(\nabla u + \nabla u^T) - \frac{2}{3} \nabla \cdot u \bar{\bar{I}} \right] u \right\}$$

contributes to internal heat generation in the flow due to viscous work between fluid layers that have relative velocity between each other. This is an irreversible work that is transformed into heat. However, this term is usually negligible is the major part of the flows. Two main factors characterize this term: fluid viscosity and velocity gradients. This is why the inclusion of this term is normally only important in compressible flows where very high velocities (and thus gradients) are developed, i.e. high Mach-number flows. In flows with high viscosity fluids it can also be important to include this term. In this case, the air doesn't have high viscosity and the velocity isn't high so isn't necessary to include this term. According to [9], this term should be included when Brinkman adimensional number approaches or exceeds the unity.

$$Br = \frac{\mu U_e^2}{\lambda \Delta T} \tag{3.19}$$

Velocities within the system are of the order of some mm s-1 or cm s-1, and temperature difference in the system is of the order of some degrees. This gives an order of magnitudes of around 10-4 to 10-6, thus the inclusion of this term is totally unnecessary as it has been predicted.

3.3.3. On the Boussinesq approximation to model buoyancy driven flow

Due to heat loss to the surroundings and inflow thermal properties the temperature and thus the density is not uniform inside the room. In other words, the fluid and flow are compressible.

However, in this work (and in most of similar works that can be found in references) Boussinesq approximation is used for air. This approximation assumes incompressible flow due to low variations in density that makes small difference in the governing equations.

However, the effect on the gravitational force term is important and thus is considered in this approximation. This approximation is rather popular in buoyancy driven flow where temperature differences are not very high.

4. PROCESS AND RESULTS

4.1. DESCRIPCION AND SPECIFICATIONS OF THE PHYSICAL BOUNDARIES

The description of the physical boundaries in the study case consists of the figure of the human body, room side-walls and the parameters of the inlet and the outlet, in other words, the envelope of the fluid.

The shape of the manikin was slightly simplified from that of a real human body with feet and arms put together, close to the body (Fig. 5.1), under the consideration of keeping the balance of simulation load and precision. The manikin has a height of 1.65 m and thus a surface area of 1.7 m^2

The walls around the room were adiabatic for both heat and moisture, assuming that the placement of the room would be in the interior part of a building. The measurements of the room are 4 metres wide and 3 metres of high.

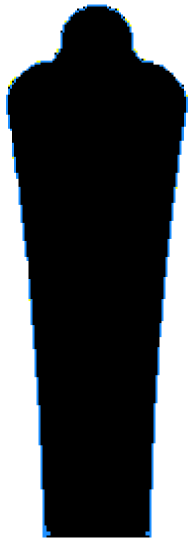

Fig 4. 1 Manikin's shape

The room was air-conditioned in order to remove the heat and moisture production from the manikin. A displacement ventilation system was used to achieve the stagnant flow field in the room space.
In the cases with cooling the supply temperature is 22ºC, and the supply velocity is 2 m/s. For the cases without cooling the supply temperature is 28ºC and the supply velocity is the same than in the cooling cases. The supply and exhaust opening has a diameter of 0.3 meters. The supply opening is on the top-left of the room and the exhaust opening is situated on the bottom-right

4.2. RESULTS

Next I'm going to show the results of the different cases that I have studied but the comments in each case will be added in the next section where I have done some comparisons in order to obtain conclusions more clearly.

There are 3 kinds of graphics in each case:

- Temperature of the air in the room.
- Velocity vectors of the air, which shows the route of the fluid in the room
- A comparison of the temperature of the clothing and the temperature of the skin

CASE 1

Regime	Clothing	Activity
Cooling	0.37 clo	Sedentary activity: 1.2 met

Air temperature:

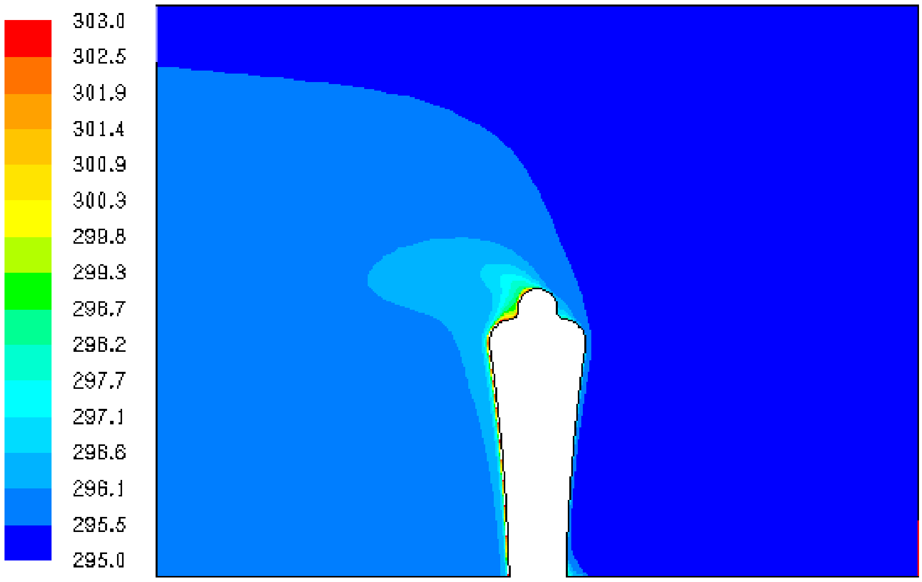

Fig 4. 2 Air temperature case 1 (K)

Velocity vectors:

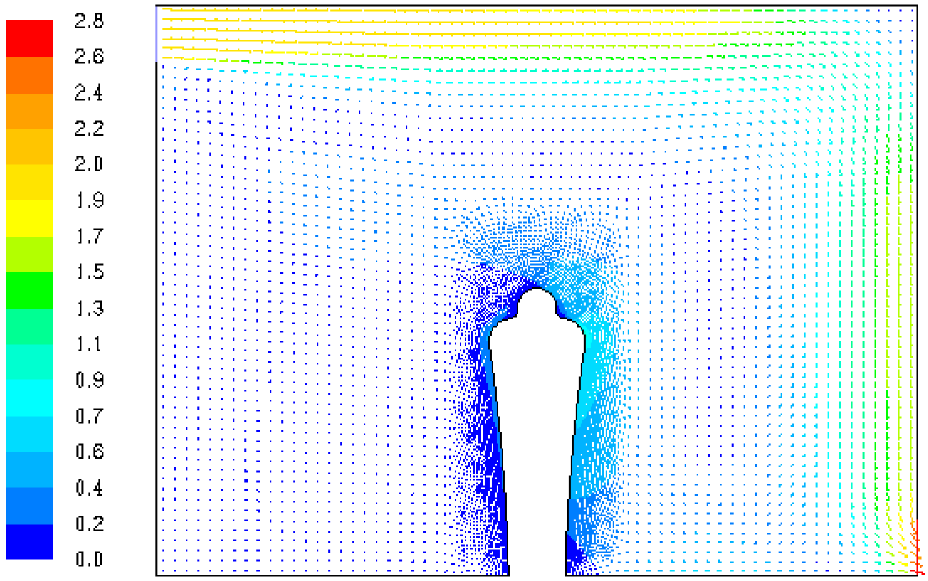

Fig 4. 3 Velocity vectors case 1 (m/s)

Comparison T_{skin} -$T_{clothing}$

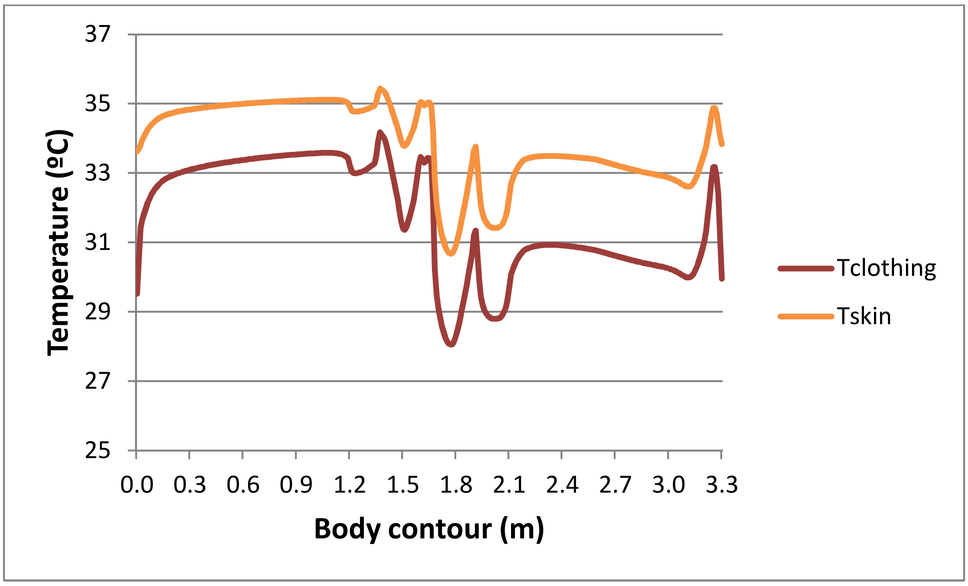

Fig 4. 4 Tskin vs Tclothing case 1 (ºC)

CASE 2

Regime	Clothing	Activity
Cooling	0.37 clo	Teaching, lab work:1.6 met

Air temperature:

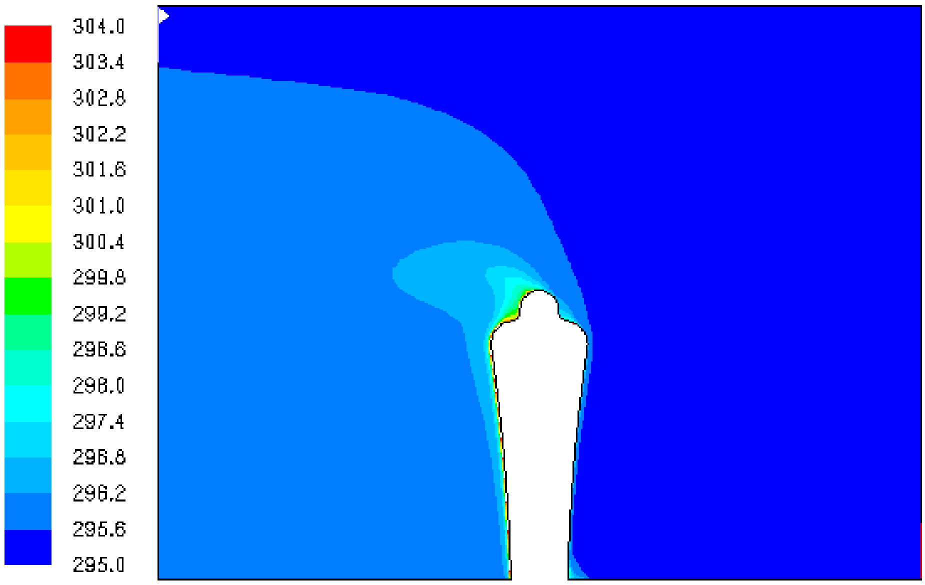

Fig 4. 5 Air temperature case 2 (K)

Velocity vectors:

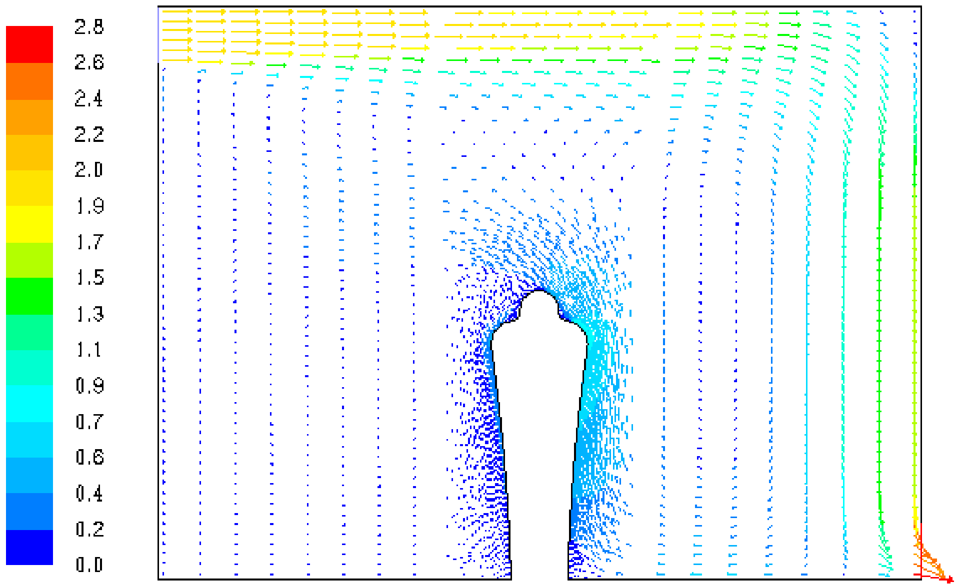

Fig 4. 6 Velocity vectors case 2 (m/s)

Comparison T_{skin} -$T_{clothing}$

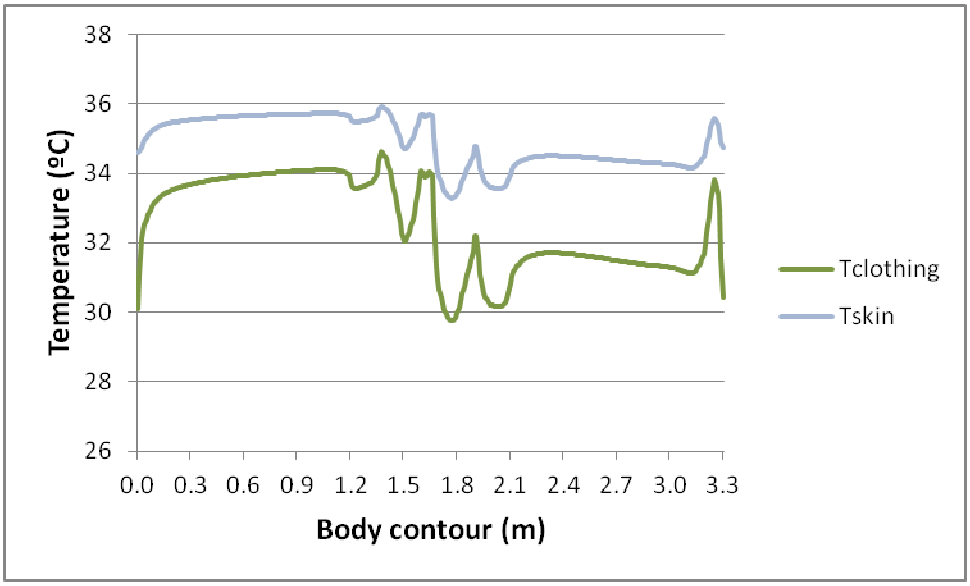

Fig 4. 7 Tskin vs Tclothing case 2 (ºC)

CASE 3

Regime	Clothing	Activity
Cooling	0.37 clo	Medium activity: 2.0 met

Air temperature:

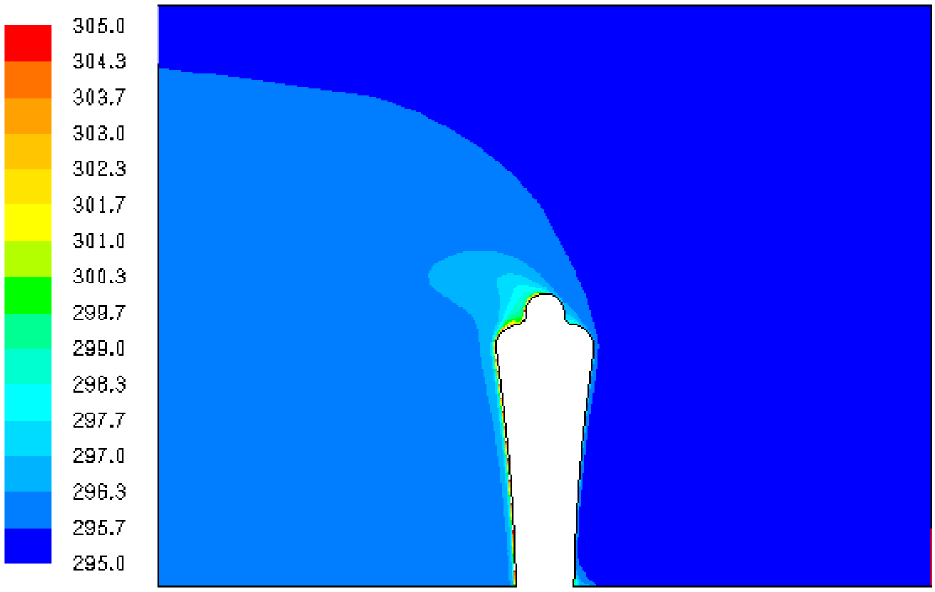

Fig 4. 8 Air temperature case 3 (K)

Velocity vectors:

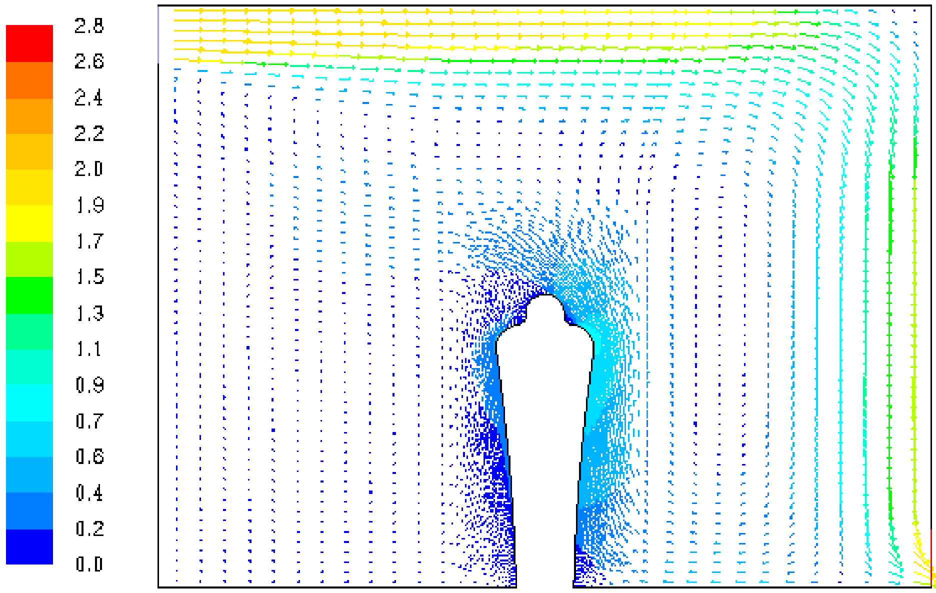

Fig 4. 9 Velocity vectors case 3 (m/s)

Comparison T_{skin} -$T_{clothing}$

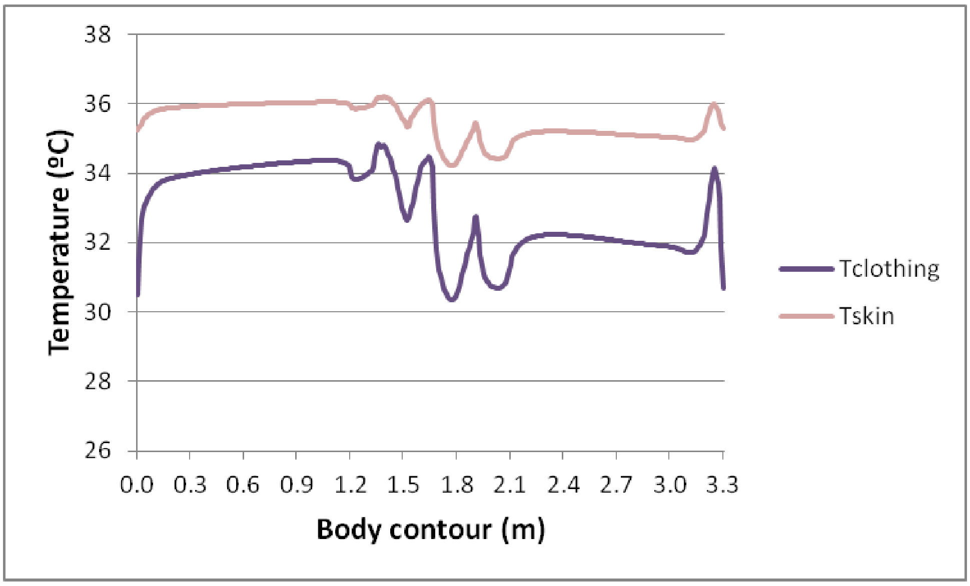

Fig 4. 10 Tskin vs Tclothing case 3 (ºC)

CASE 4

Regime	Clothing	Activity
Cooling	0.37 clo	Ironing: 3 met

Air temperature:

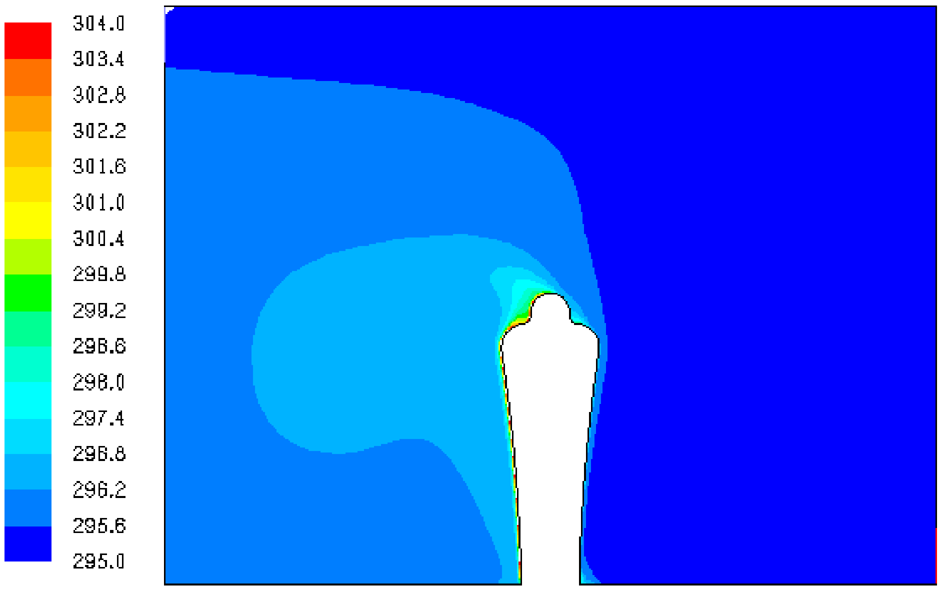

Fig 4. 11 Air temperature case 4 (K)

Velocity vectors:

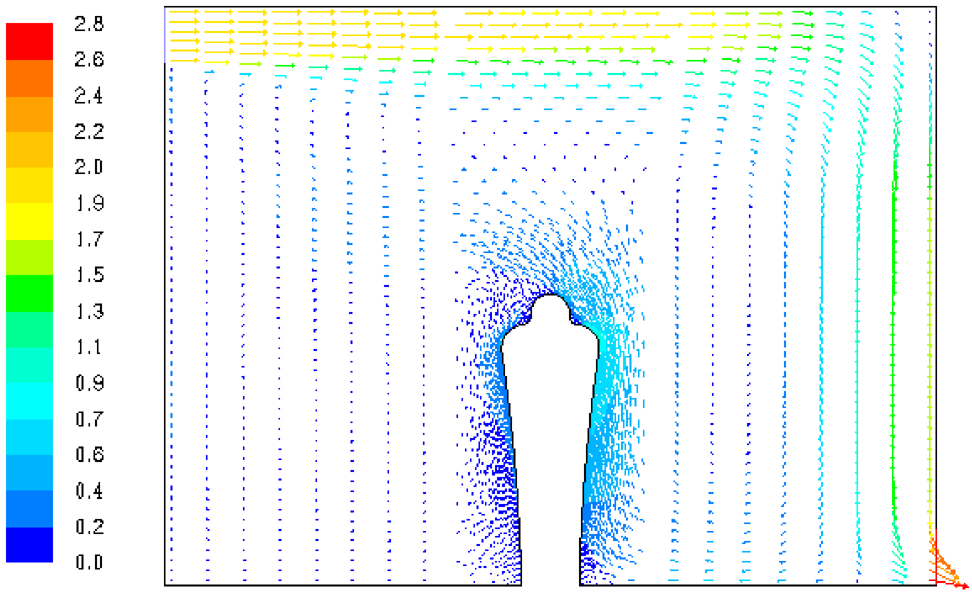

Fig 4. 12 Velocity vectors case 4 (m/s)

Comparison T_{skin} -$T_{clothing}$

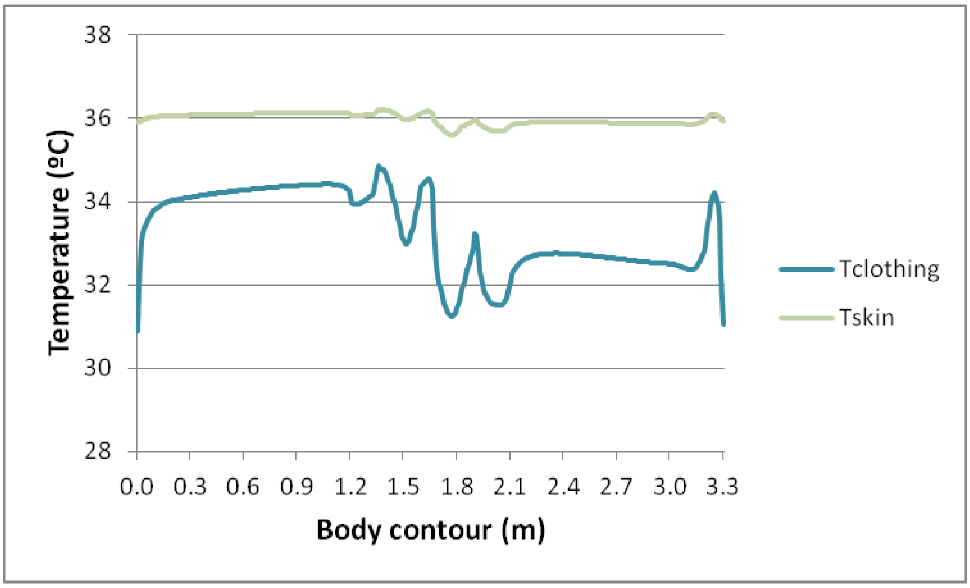

Fig 4. 13 Tskin vs Tclothing case 4 (ºC)

CASE 5

Regime	Clothing	Activity
Cooling	0.37 clo	Aerobic, dancing: 6 met

Air temperature:

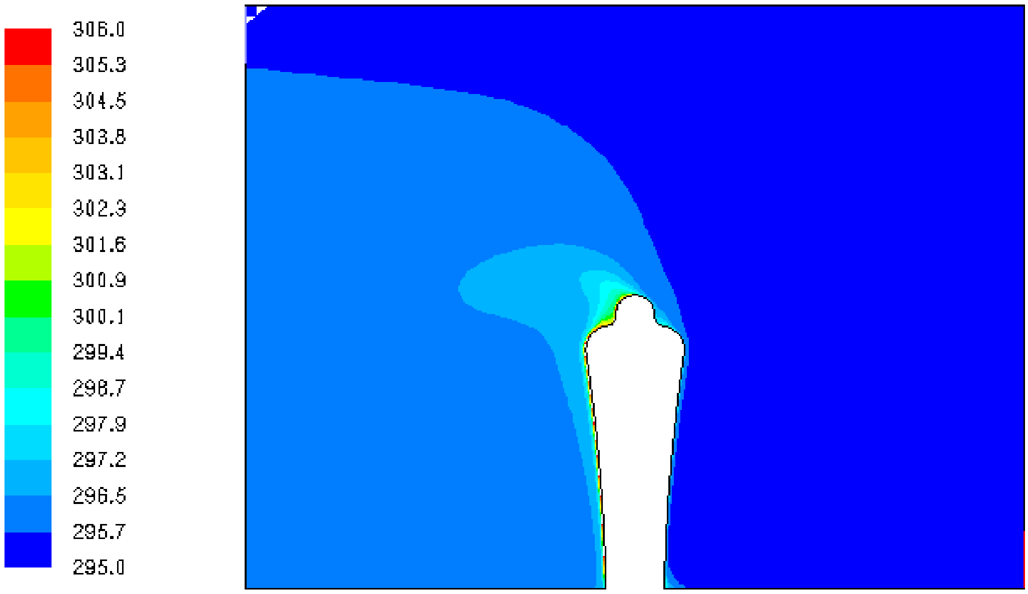

Fig 4. 14 Air temperature case 5 (K)

Velocity vectors:

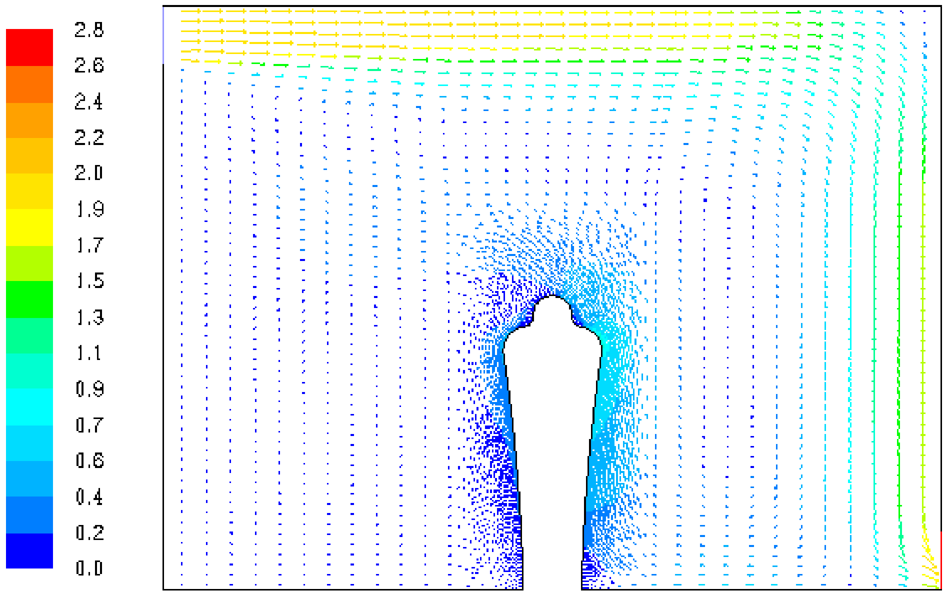

Fig 4. 15 Velocity vectors case 5 (m/s)

Comparison T_{skin} -$T_{clothing}$

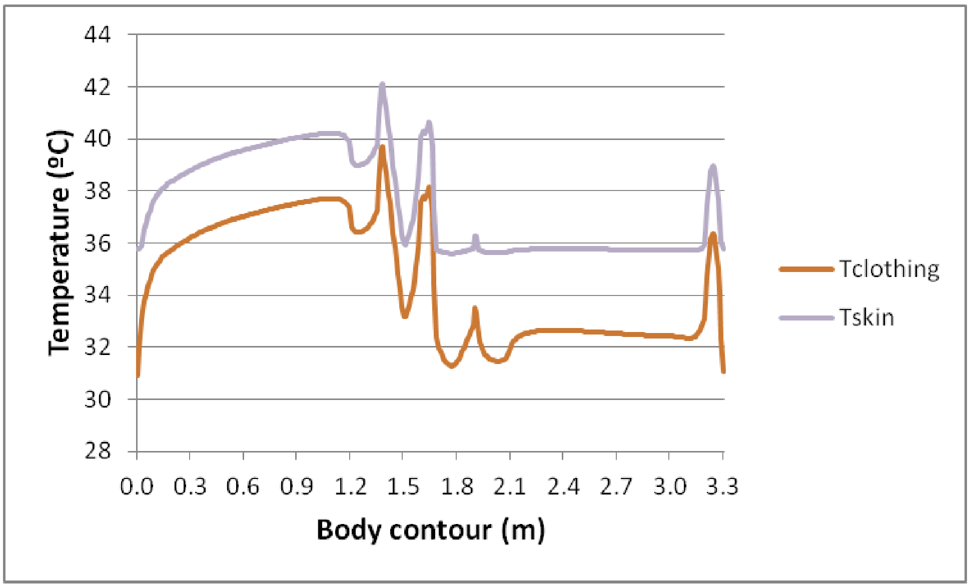

Fig 4. 16 Tskin vs Tclothing case 5 (ºC)

CASE 6

Regime	Clothing	Activity
Cooling	0.60 clo	Sedentary activity: 1.2 met

Air temperature:

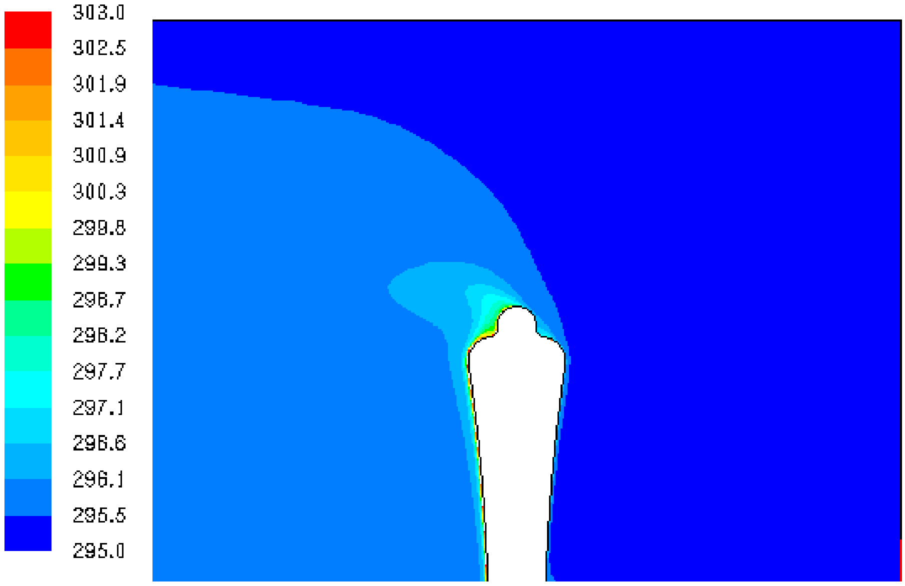

Fig 4. 17 Air temperature case 6 (K)

Velocity vectors:

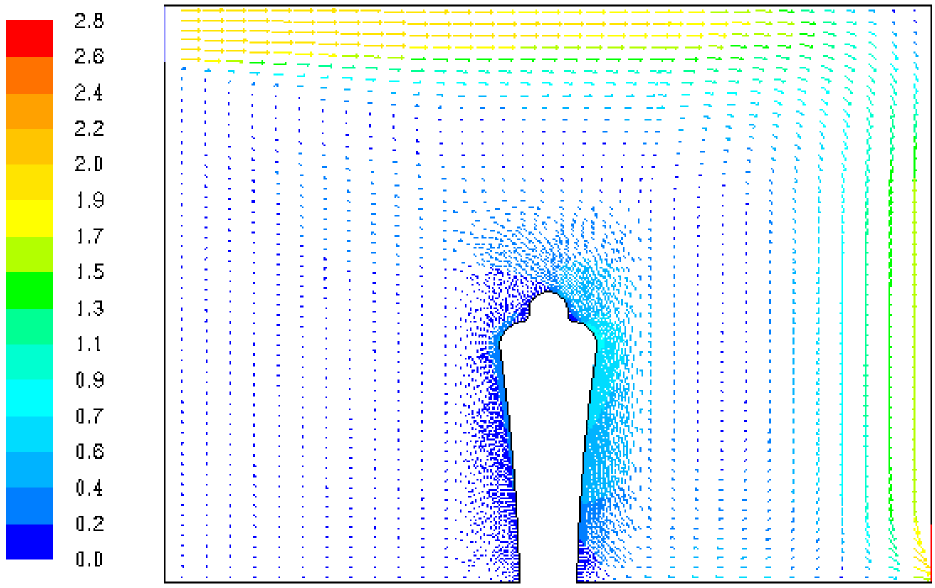

Fig 4. 18 Velocity vectors case 6 (m/s)

Comparison T_{skin} -$T_{clothing}$

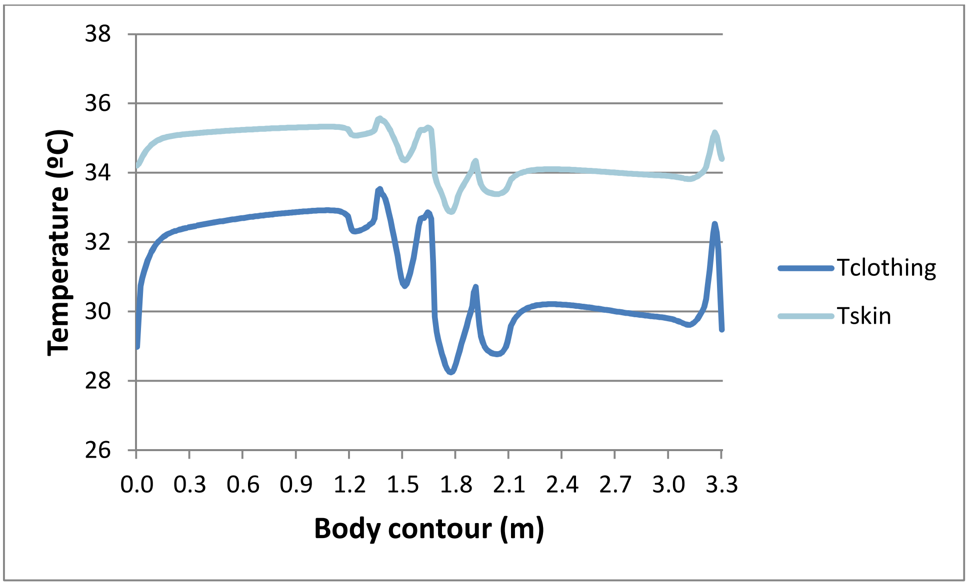

Fig 4. 19 Tskin vs Tclothing case 6 (ºC)

CASE 7

Regime	Clothing	Activity
Cooling	0.60 clo	Medium activity: 2 met

Air temperature:

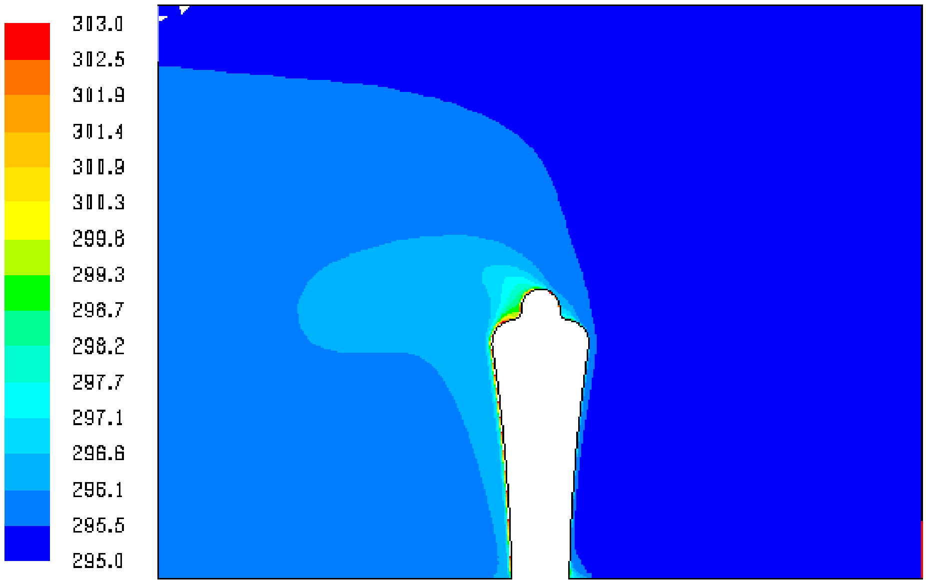

Fig 4. 20 Air temperature case 7 (K)

Velocity vectors:

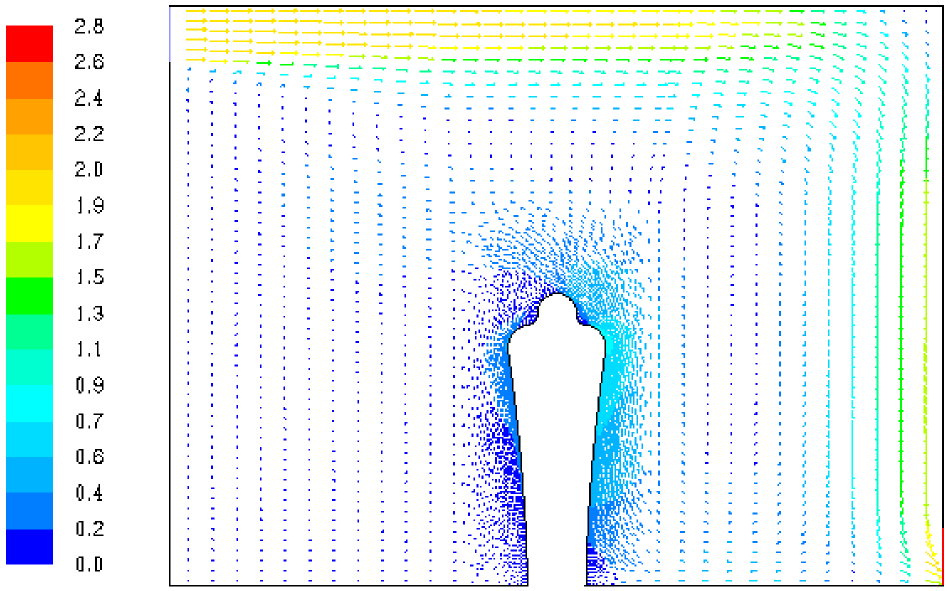

Fig 4. 21 Velocity vectors case 7 (m/s)

Comparison T_{skin} -$T_{clothing}$

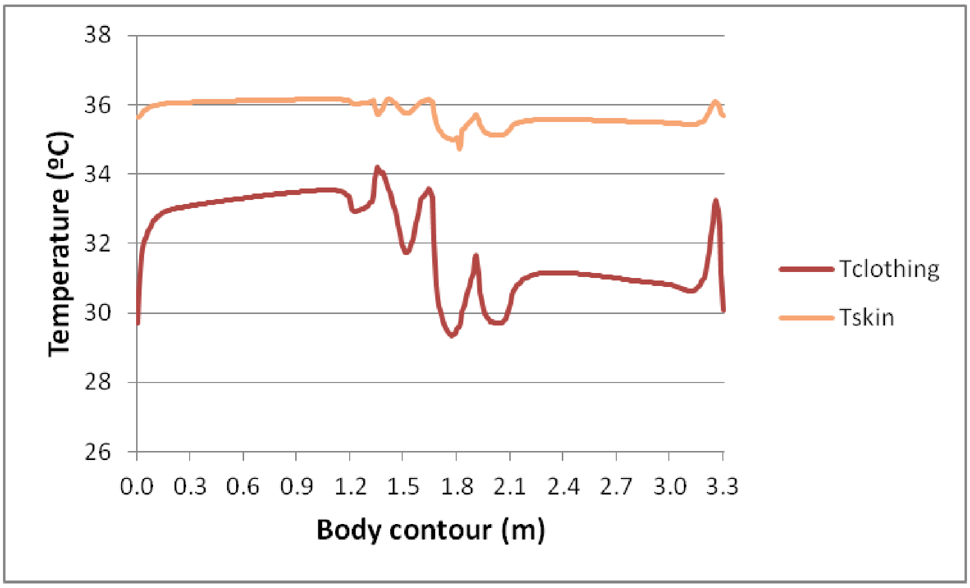

Fig 4. 22 Tskin vs Tclothing case 7 (ºC)

CASE 8

Regime	Clothing	Activity
Cooling	0.60 clo	Ironing: 3 met

Air temperature:

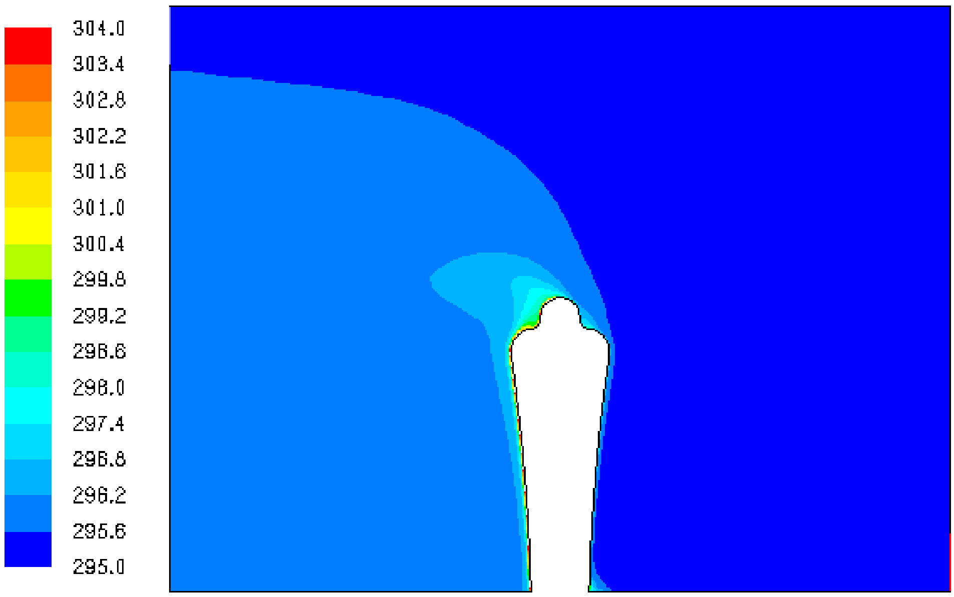

Fig 4. 23 Air temperature case 8 (K)

Velocity vectors:

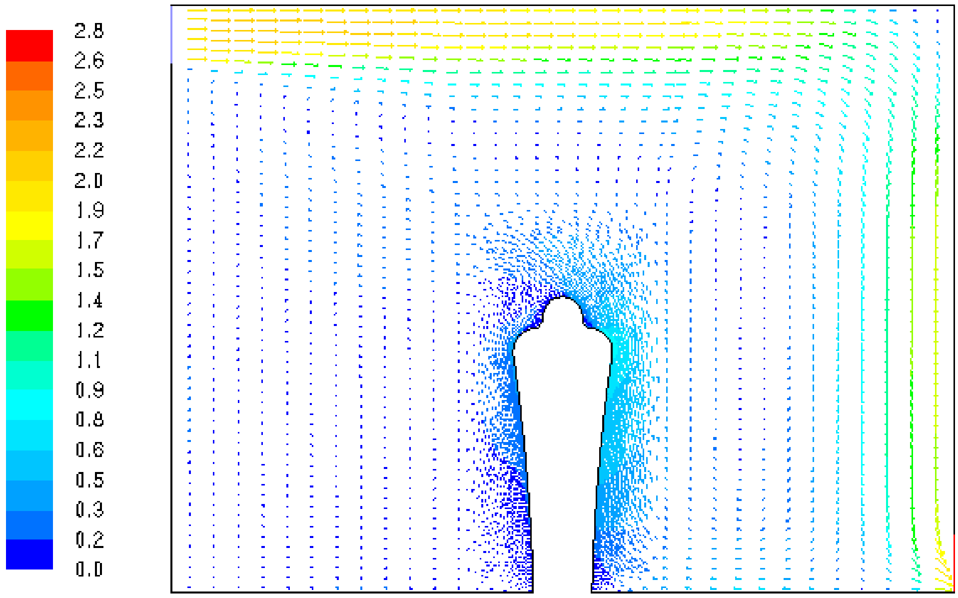

Fig 4. 24 Velocity vectors case 8 (m/s)

Comparison T_{skin} -$T_{clothing}$

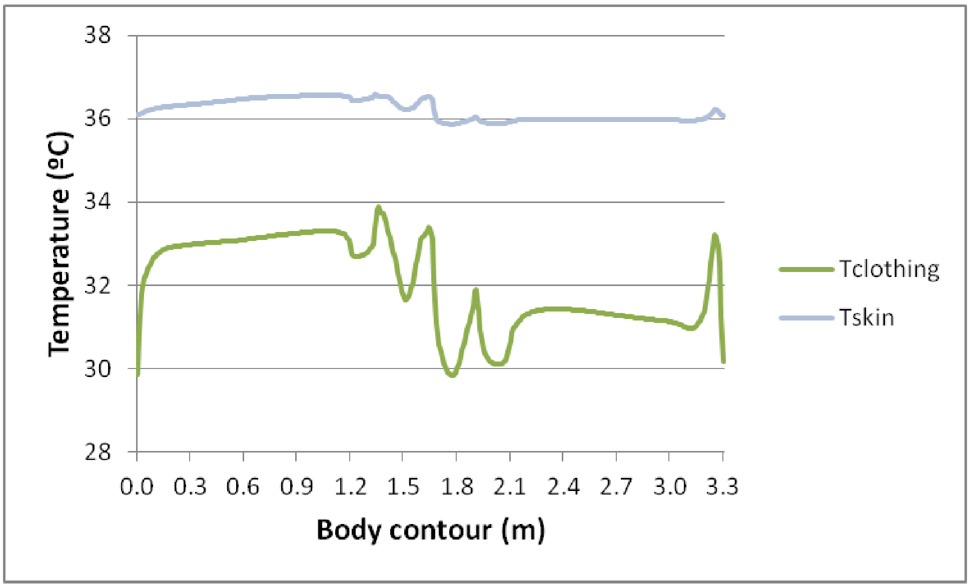

Fig 4. 25 Tskin vs Tclothing case 8 (ºC)

. CASE 9

Regime	Clothing	Activity
Cooling	0.93 clo	Sedentary activity: 1.2 met

Air temperature:

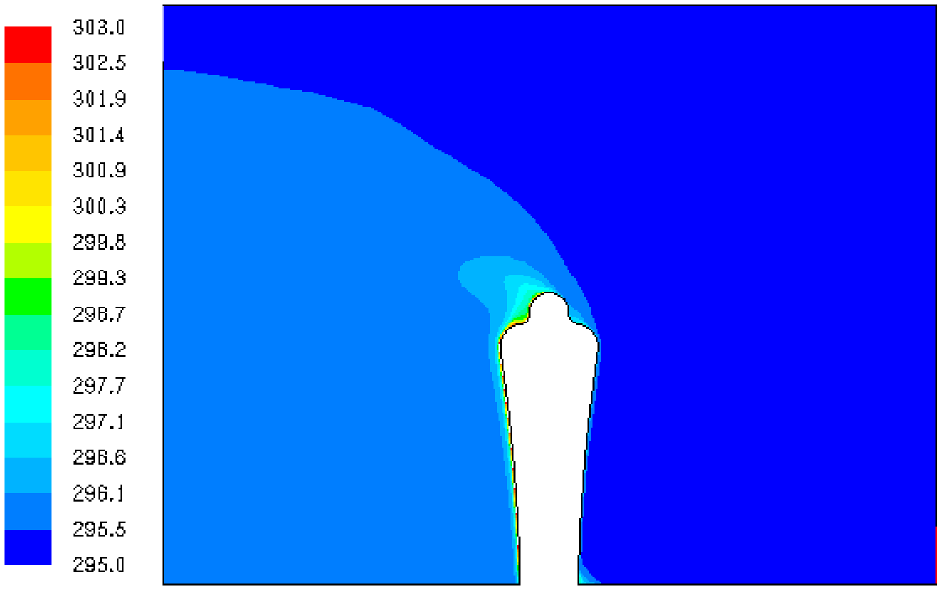

Fig 4. 26 Air temperature case 9 (K)

Velocity vectors:

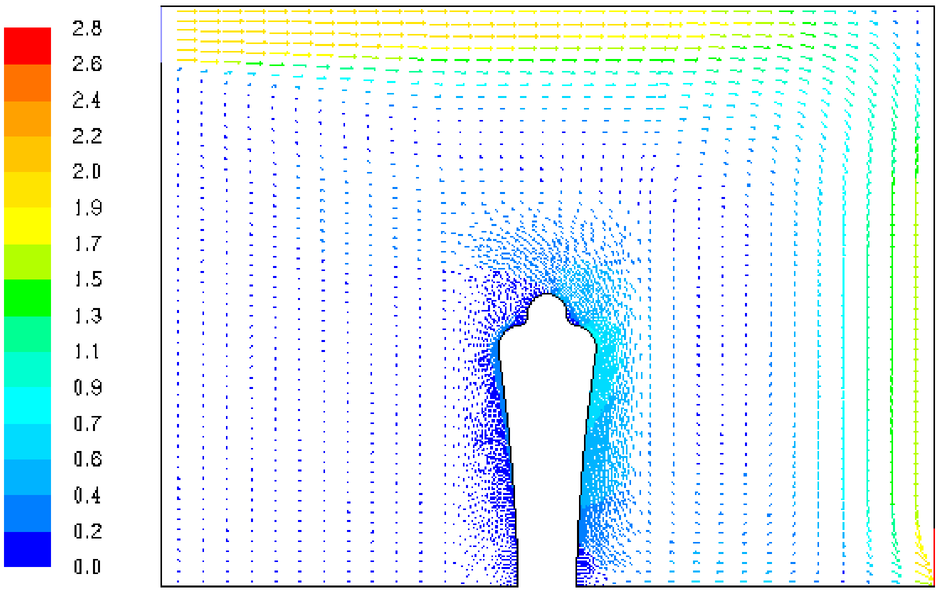

Fig 4. 27 Velocity vectors case 9 (m/s)

Comparison T_{skin} -$T_{clothing}$

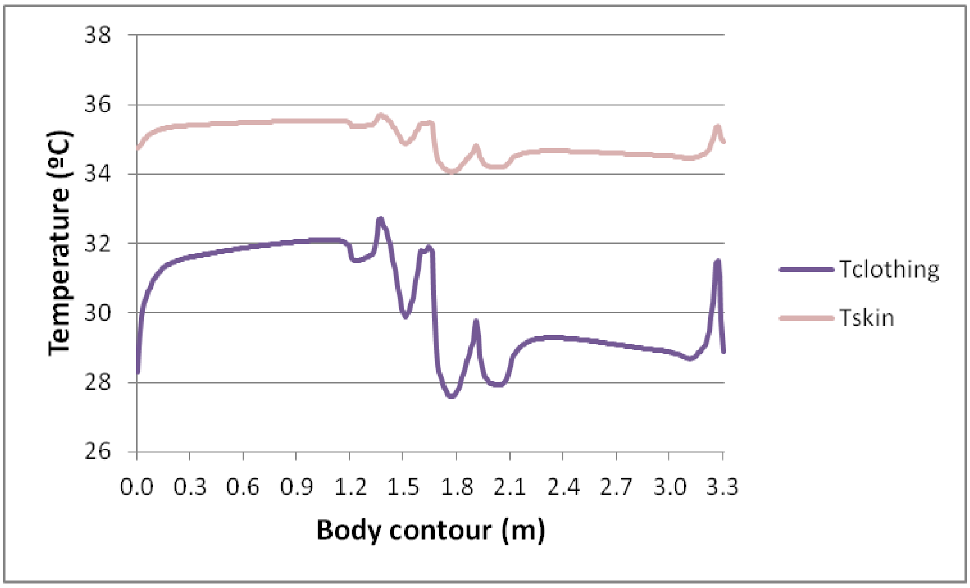

Fig 4. 28 Tskin vs Tclothing case 9 (ºC)

CASE 10

Regime	Clothing	Activity
Cooling	0.93 clo	Teaching, lab work:1.6 met

Air temperature:

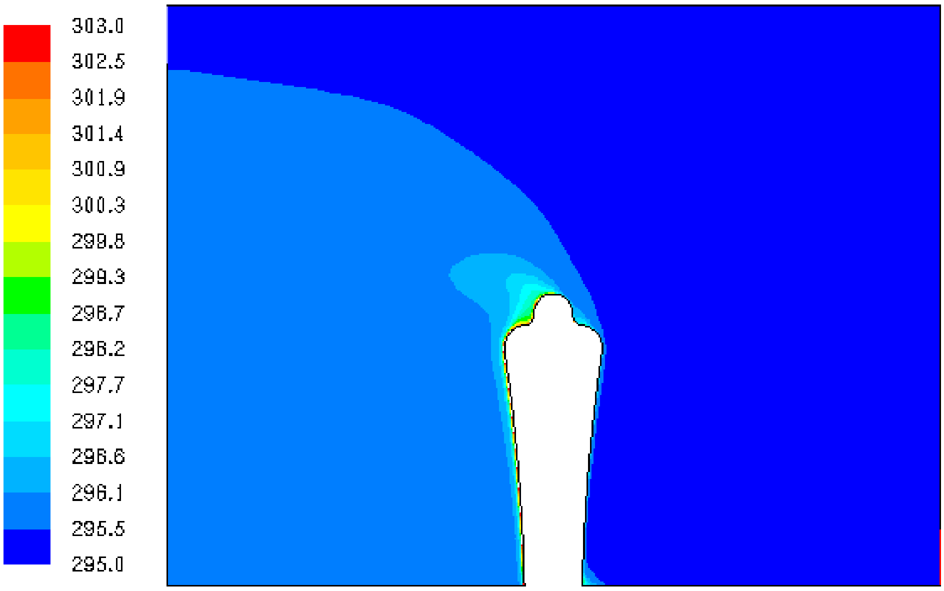

Fig 4. 29 Air temperature case 10 (K)

Velocity vectors:

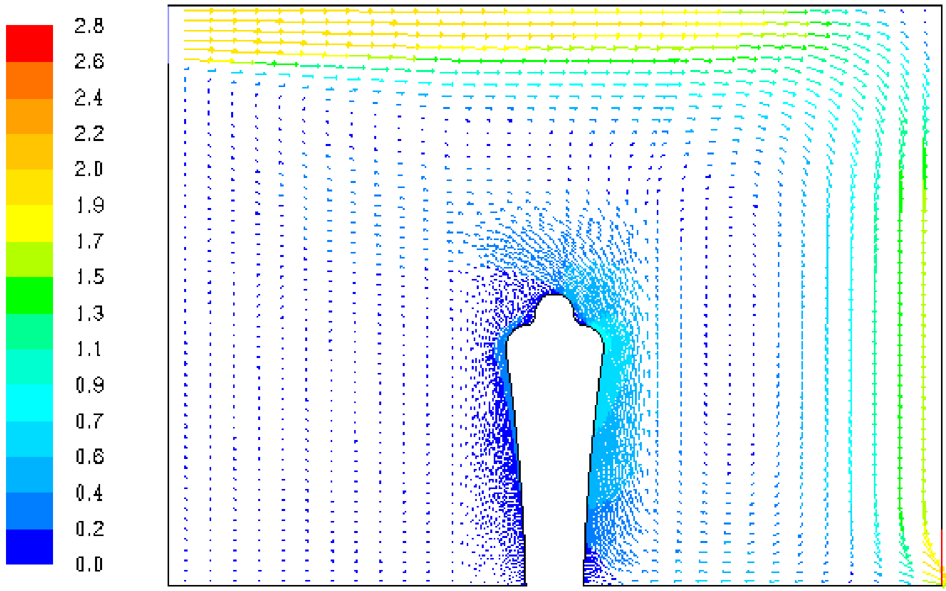

Fig 4. 30 Velocity vectors case 10 (m/s)

Comparison T_{skin} -$T_{clothing}$

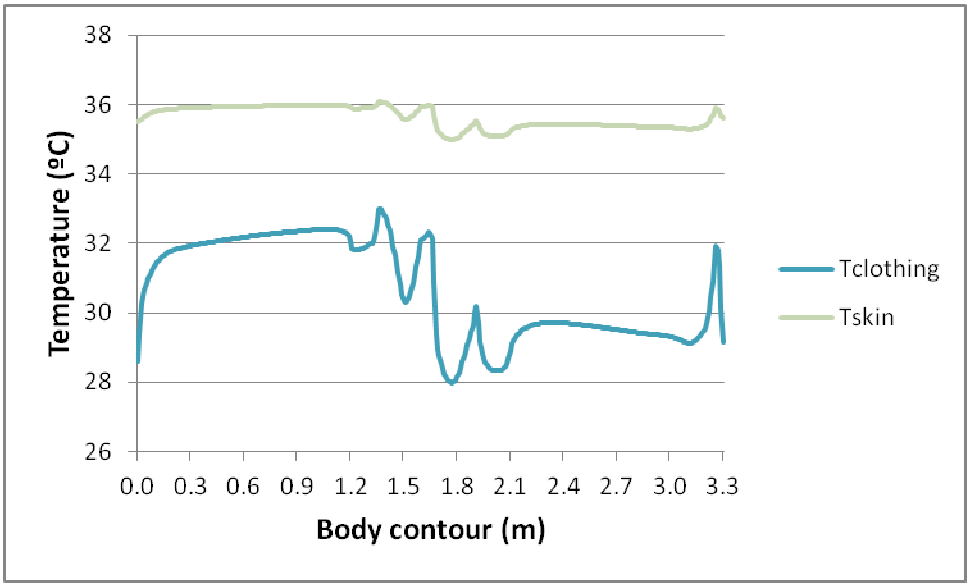

Fig 4. 31 Tskin vs Tclothing case 10 (ºC)

CASE 11

Regime	Clothing	Activity
Cooling	0.93 clo	Medium activity: 2 met

Air temperature:

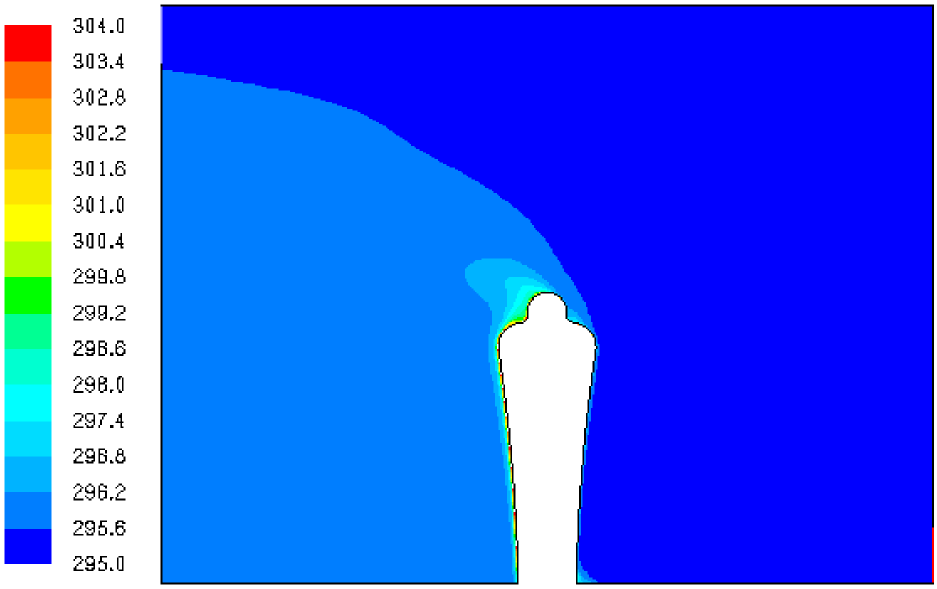

Fig 4. 32 Air temperature case 11(K)

Velocity vectors:

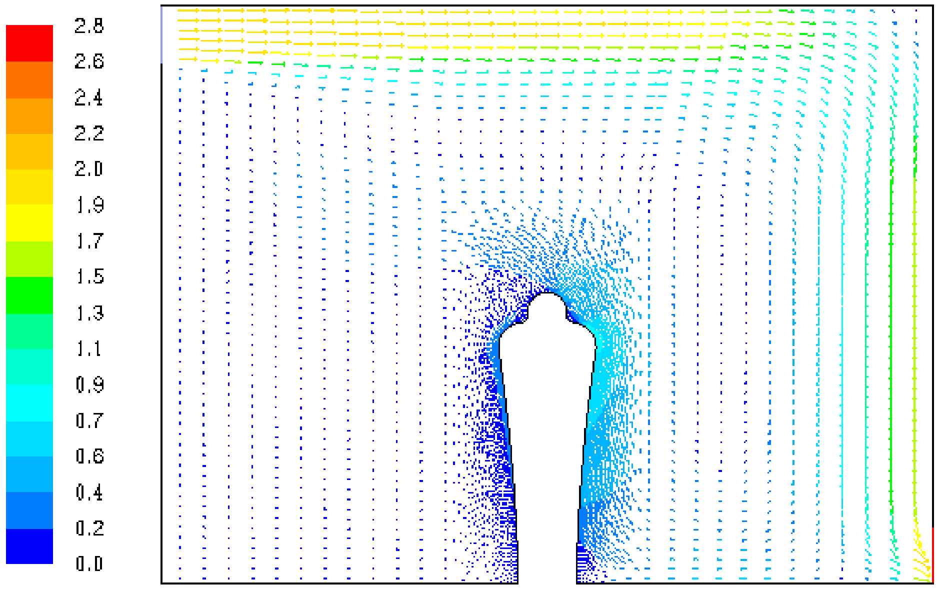

Fig 4. 33 Velocity vectors case 11 (m/s)

Comparison T_{skin} -$T_{clothing}$

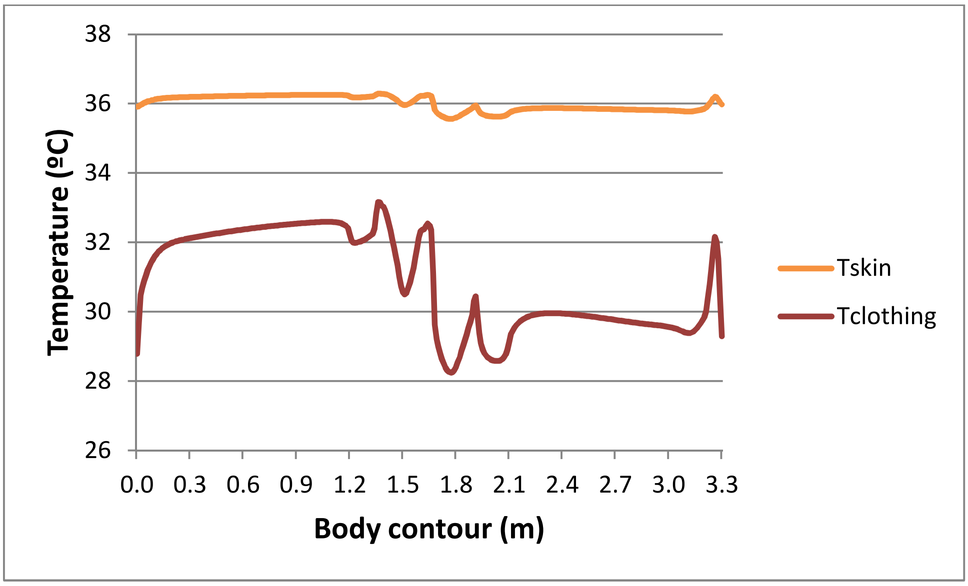

Fig 4. 34 Tskin vs Tclothing case 11 (ºC)

CASE 12

Regime	Clothing	Activity
Cooling	0.93 clo	Ironing: 3 met

Air temperature:

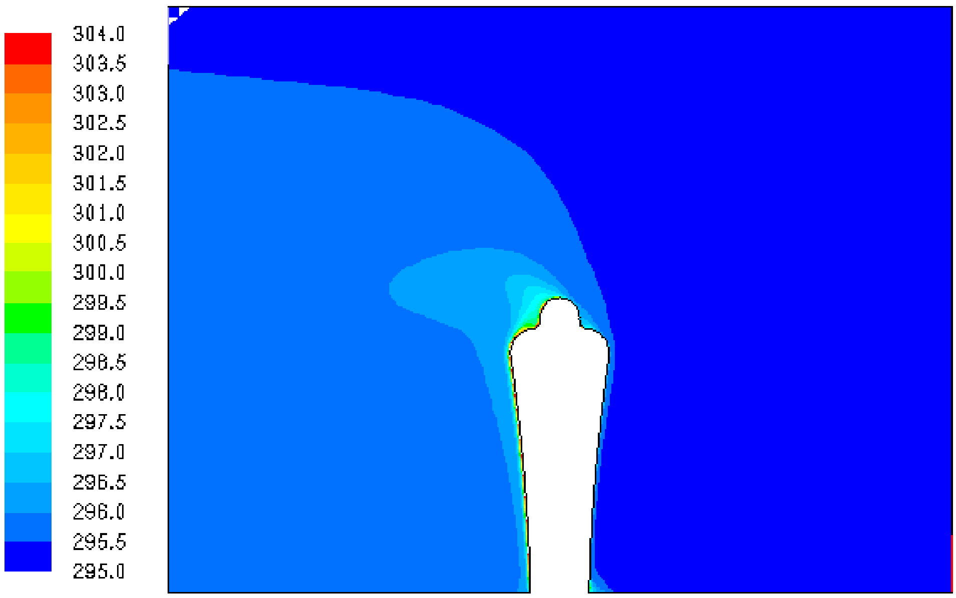

Fig 4. 35 Air temperature case 12 (K)

Velocity vectors:

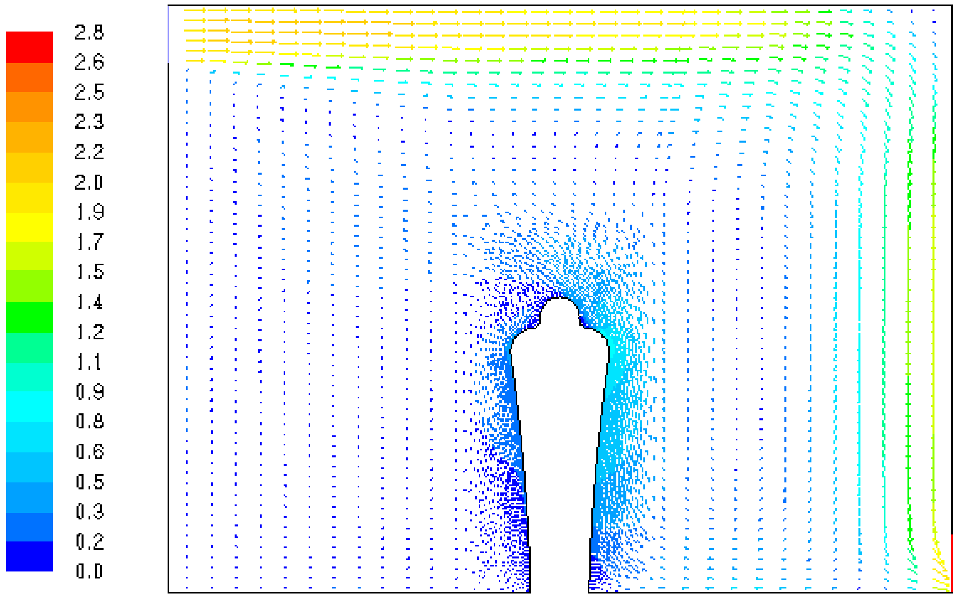

Fig 4. 36 Velocity vectors case 12 (m/s)

Comparison T_{skin} -$T_{clothing}$

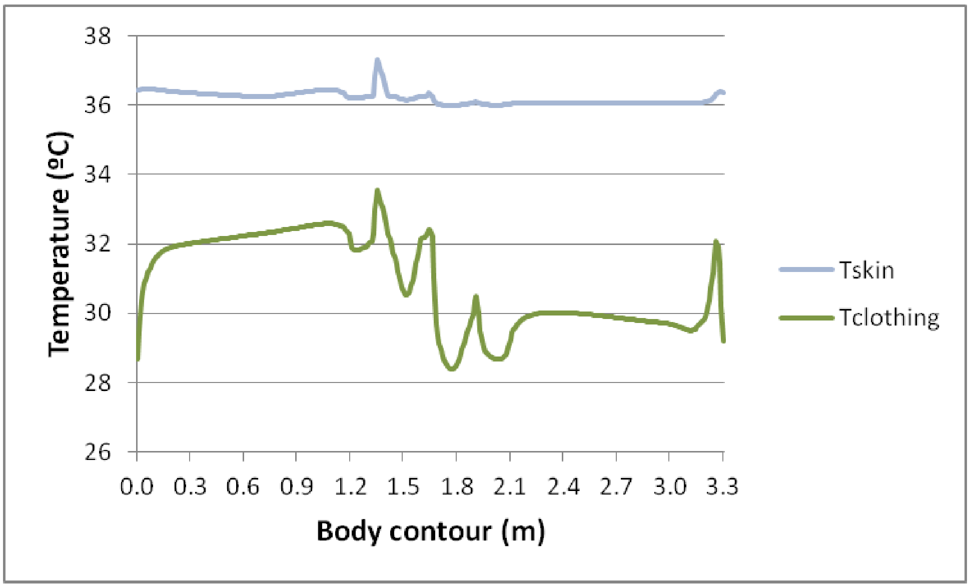

Fig 4. 37 Tskin vs Tclothing case 12 (ºC)

CASE 13

Regime	Clothing	Activity
Cooling	0.93 clo	Aerobic,dancing: 6 met

Air temperature:

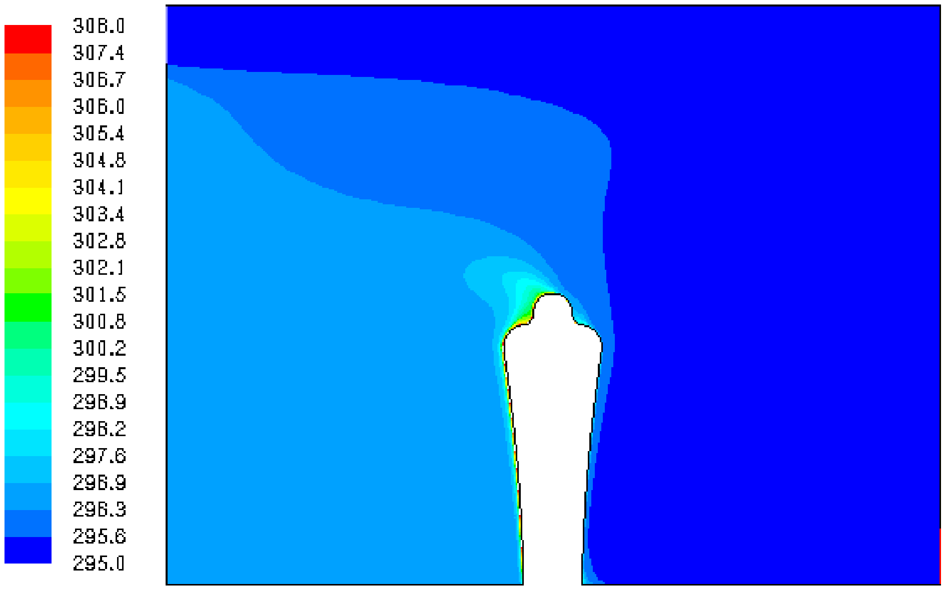

Fig 4. 38 Air temperature case 13(K)

Velocity vectors:

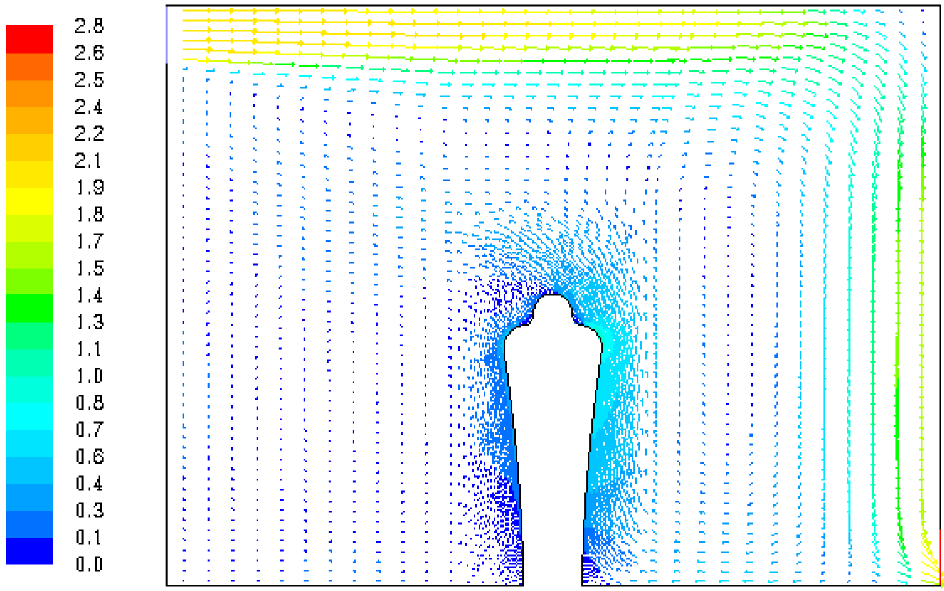

Fig 4. 39 Velocity vectors case 13 (m/s)

Comparison T_{skin} -$T_{clothing}$

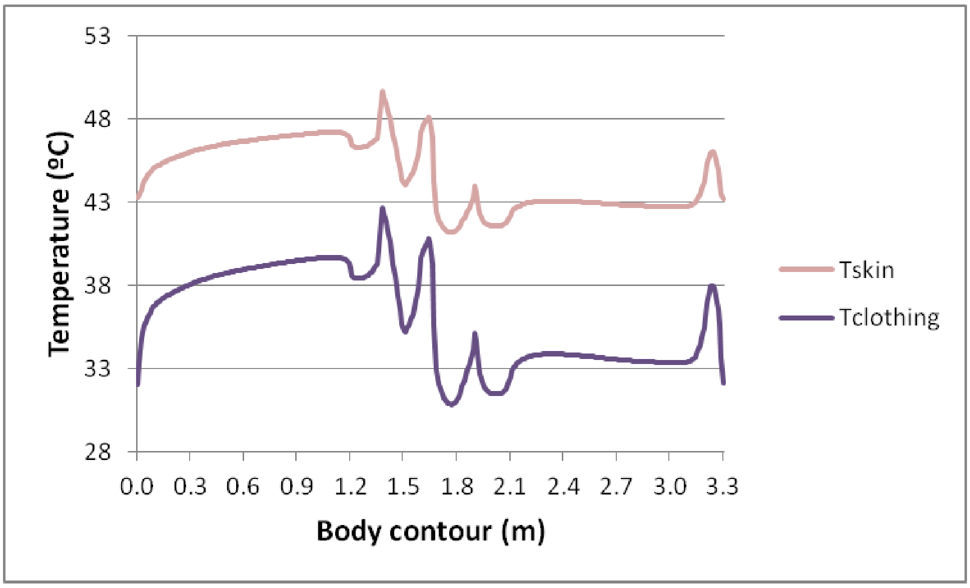

Fig 4. 40 Tskin vs Tclothing case 13 (ºC)

CASE 14

Regime	Clothing	Activity
Cooling	1.3 clo	Sedentary activity: 1.2 met

Air temperature:

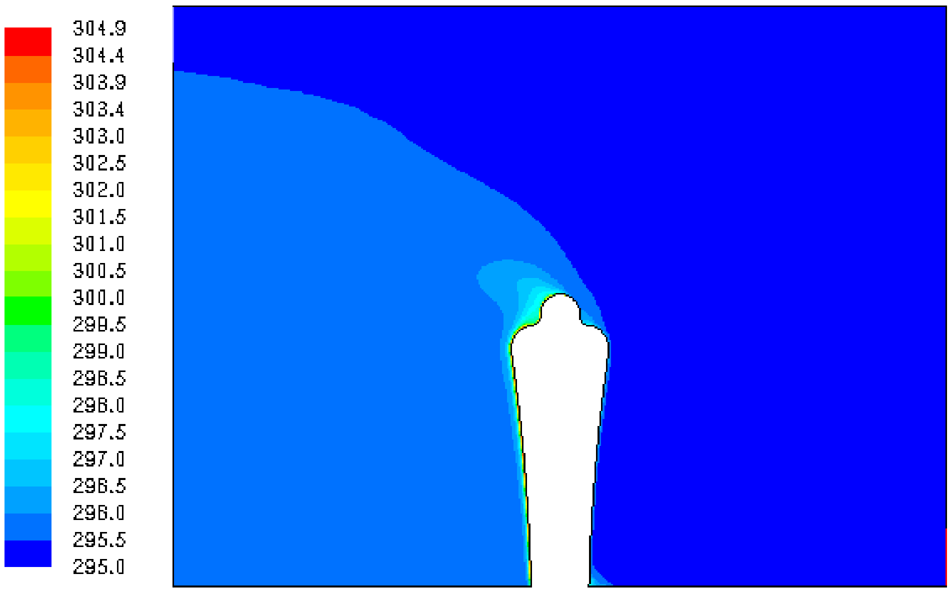

Fig 4. 41 Air temperature case 14 (K)

Velocity vectors:

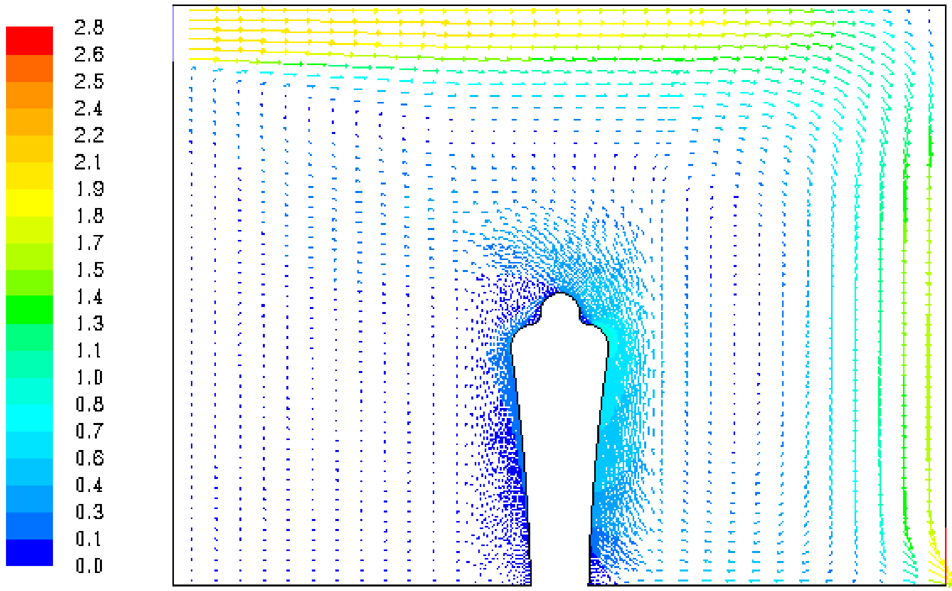

Fig 4.42 Velocity vectors case 14 (m/s)

Comparison T_{skin} -$T_{clothing}$

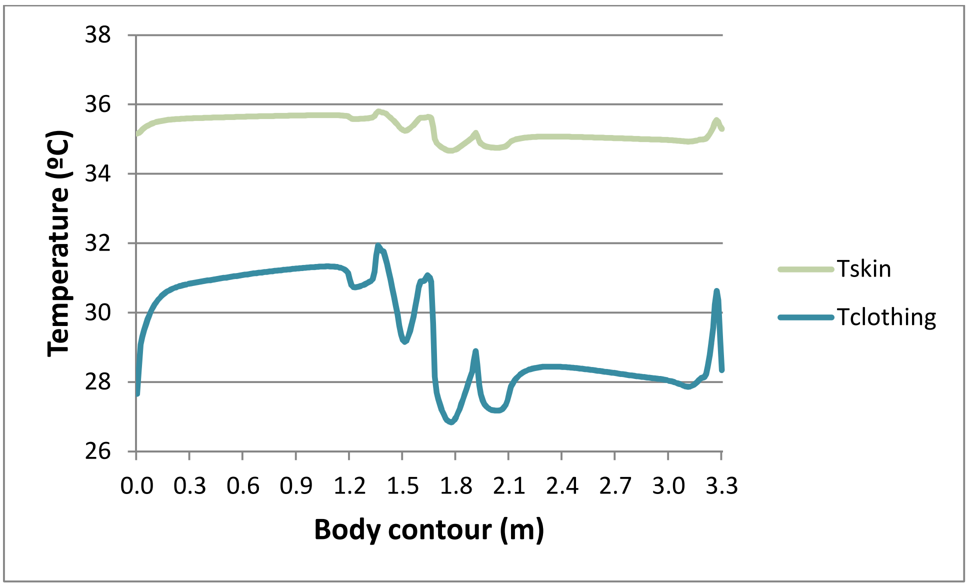

Fig 4. 43 Tskin vs Tclothing case 14 (ºC)

CASE 15

Regime	Clothing	Activity
Cooling	1.3 clo	Teaching, lab work:1.6 met

Air temperature:

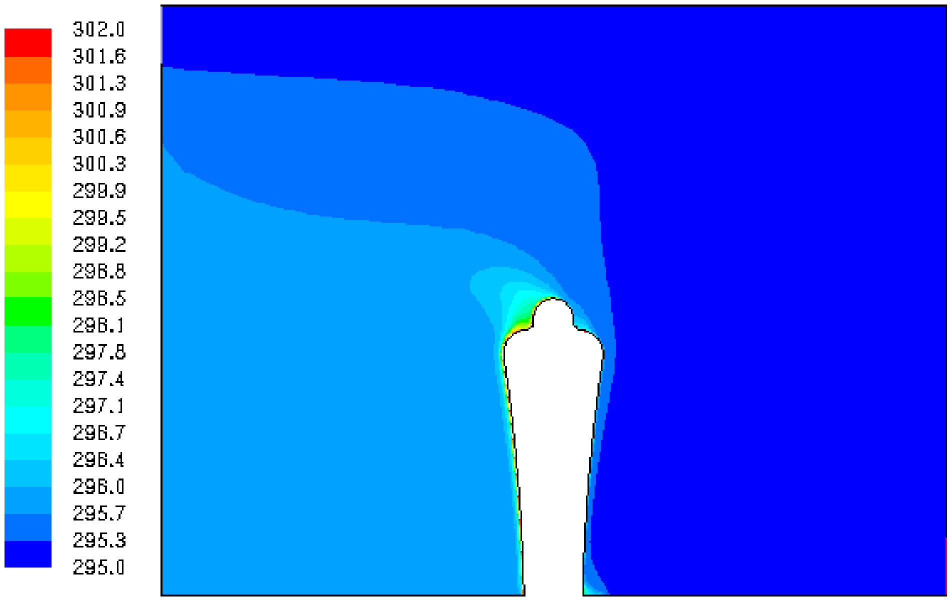

Fig 4. 44 Air temperature case 15 (K)

Velocity vectors:

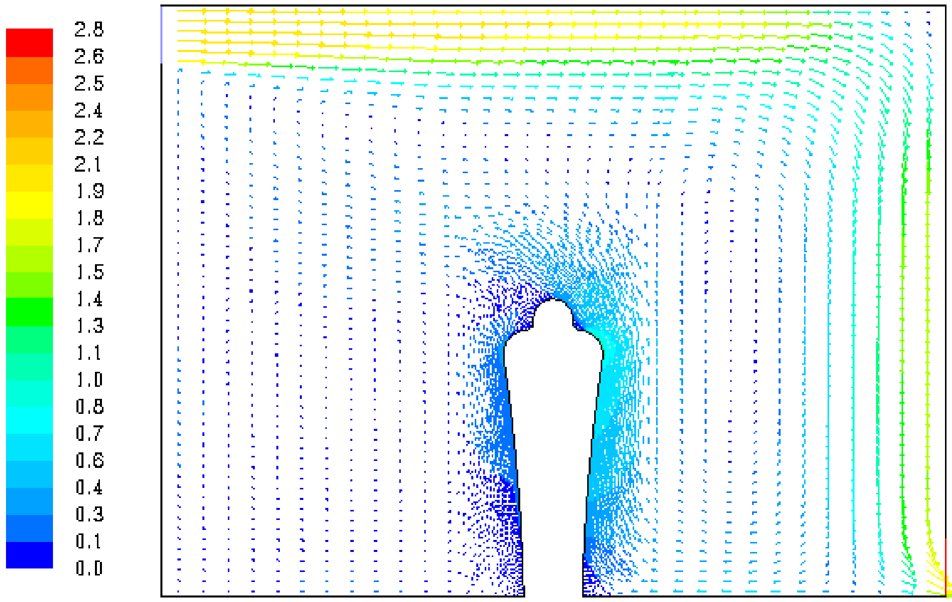

Fig 4. 45 Velocity vectors case 15 (m/s)

Comparison T_{skin} -$T_{clothing}$

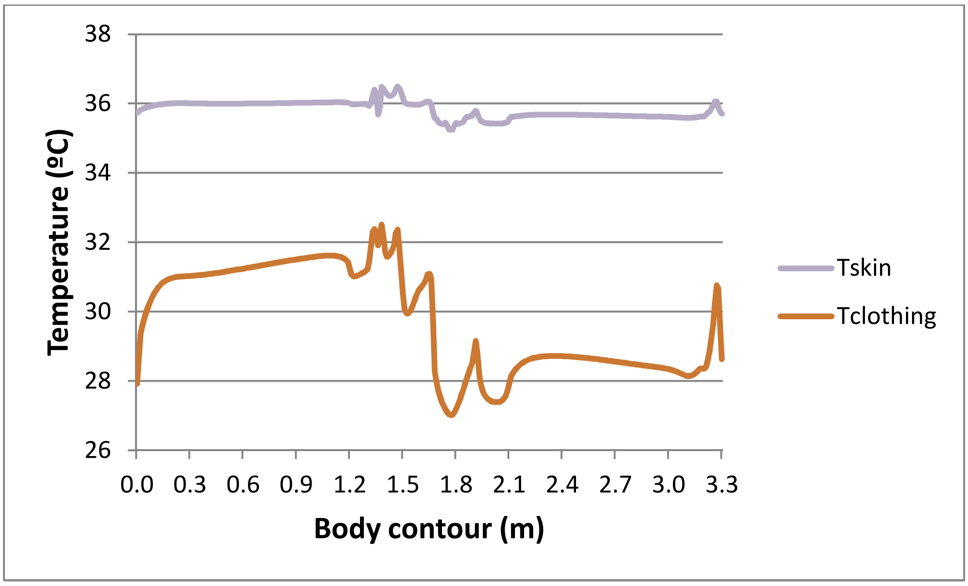

Fig 4. 46 Tskin vs Tclothing case 15 (ºC)

CASE 16

Regime	Clothing	Activity
Cooling	1.3 clo	Medium activity: 2 met

Air temperature:

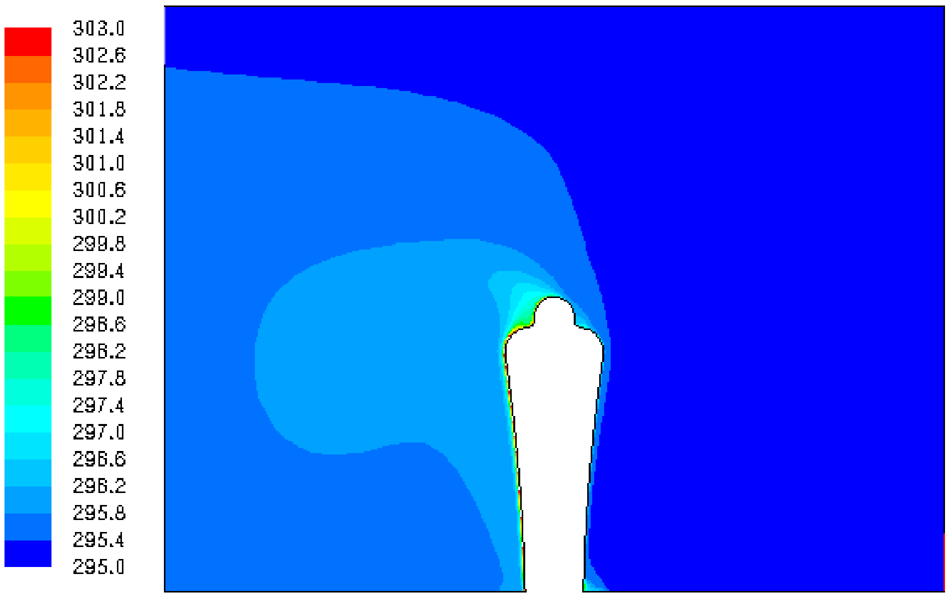

Fig 4. 47 Air temperature case 16 (K)

Velocity vectors:

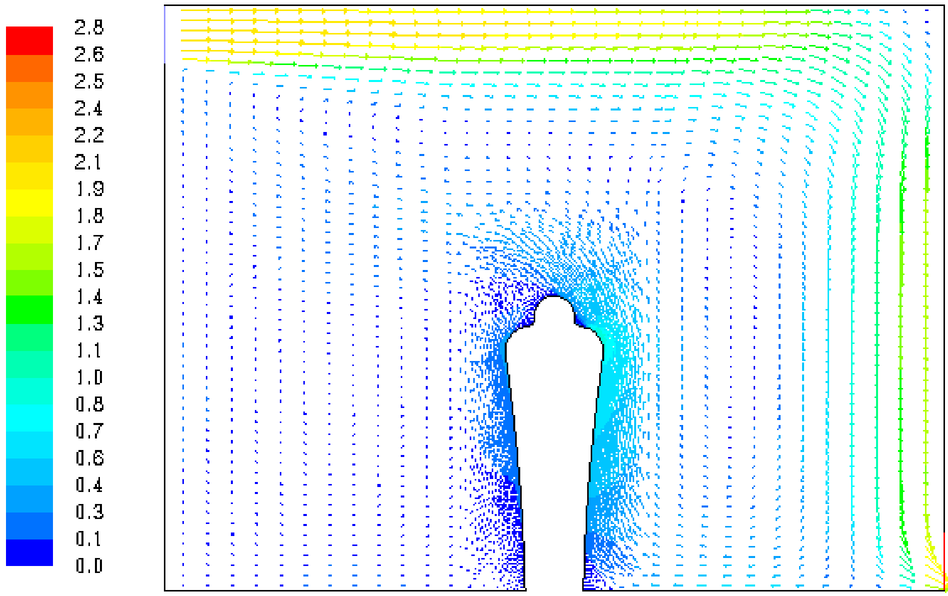

Fig 4. 48 Velocity vectors case 16 (m/s)

Comparison T_{skin} -$T_{clothing}$

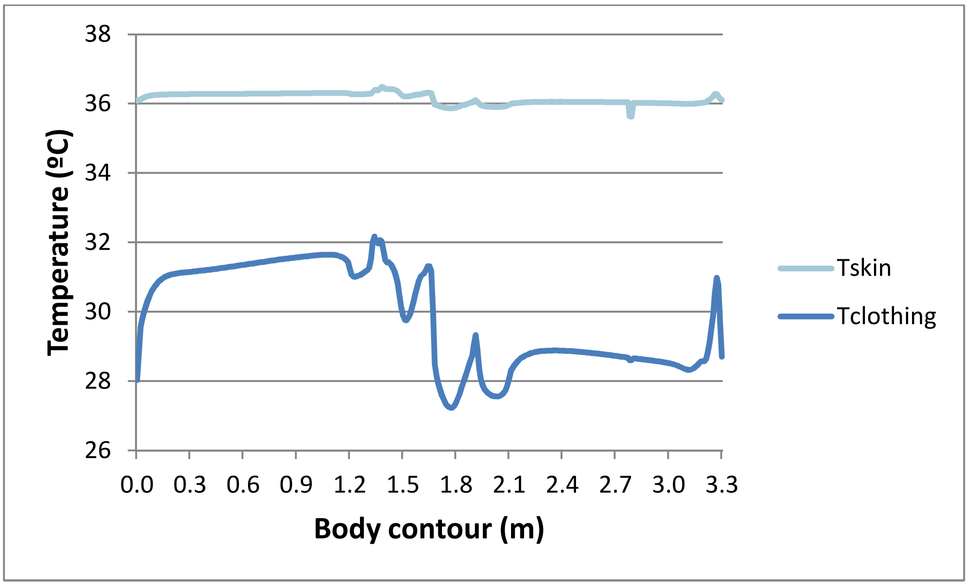

Fig 4. 49 Tskin vs Tclothing case 16 (ºC)

CASE 17

Regime	Clothing	Activity
Cooling	1.3 clo	Ironing: 3 met

Air temperature:

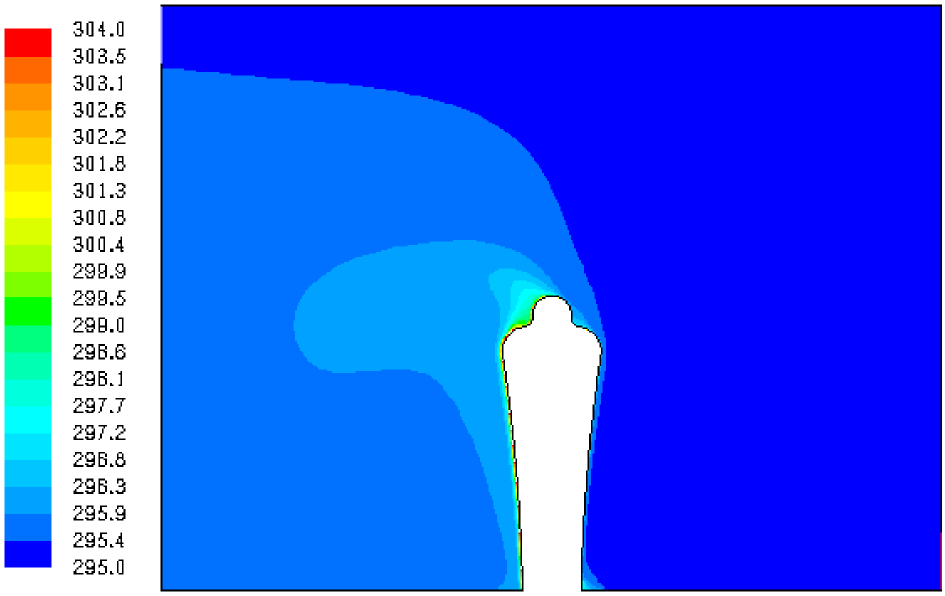

Fig 4. 50 Air temperature case 17 (K)

Velocity vectors:

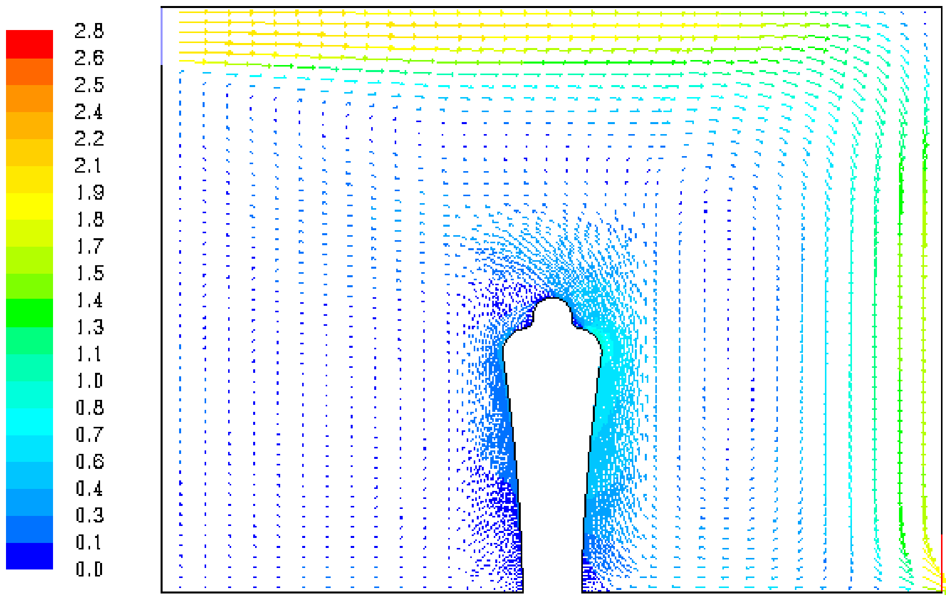

Fig 4. 51 Velocity vectors case 17 (m/s)

Comparison T_{skin} -$T_{clothing}$

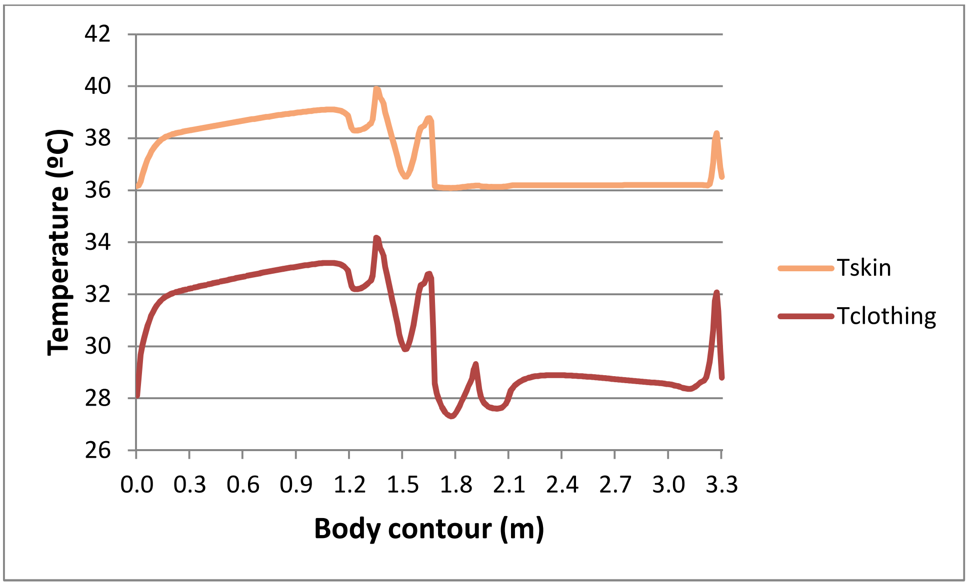

Fig 4. 52 Tskin vs Tclothing case 17 (ºC)

CASE 18

Regime	Clothing	Activity
Cooling	1.3 clo	Aerobic, dancing: 6 met

Air temperature:

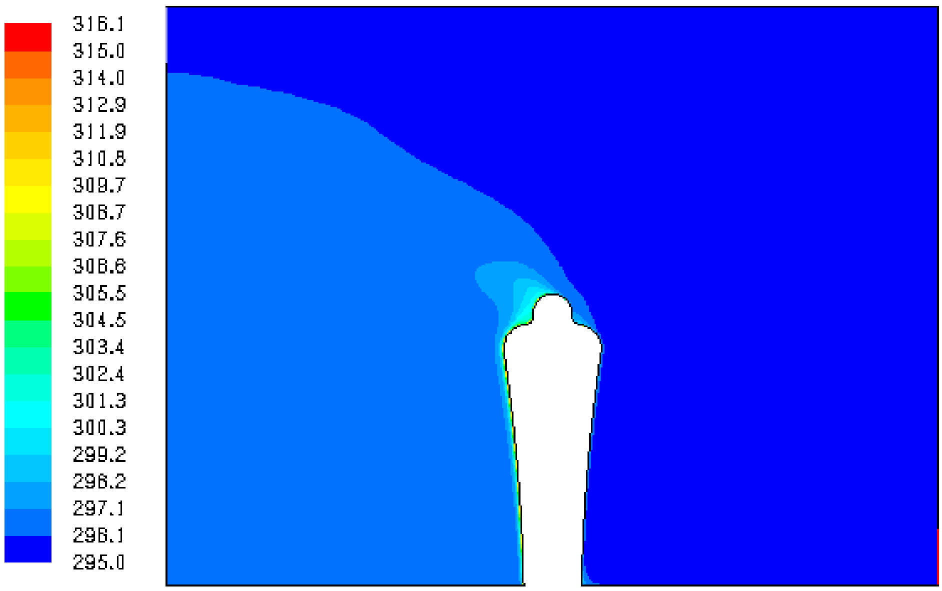

Fig 4. 53 Air temperature case 18 (K)

Velocity vectors:

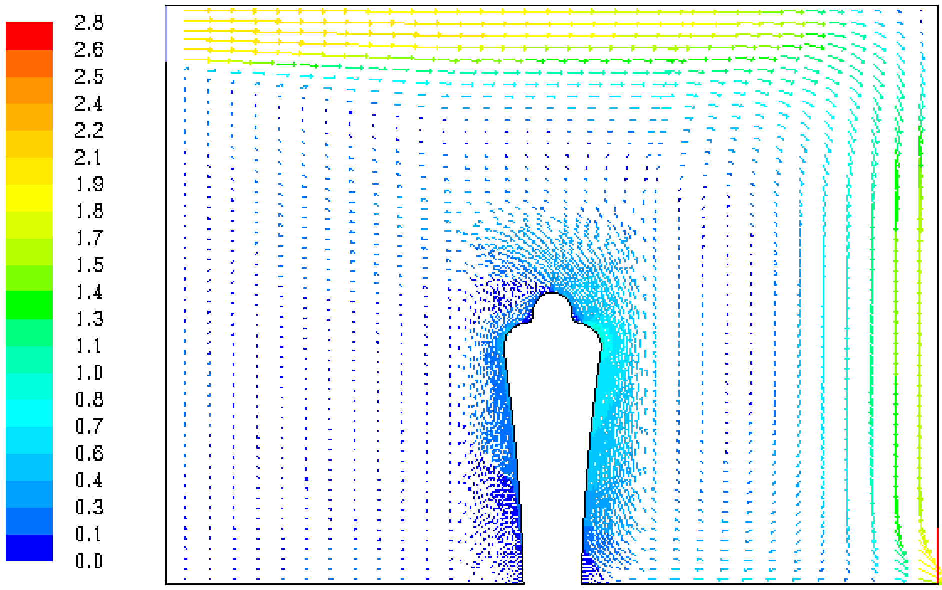

Fig 4. 54 Velocity vectors case 18 (m/s)

Comparison T_{skin} -$T_{clothing}$

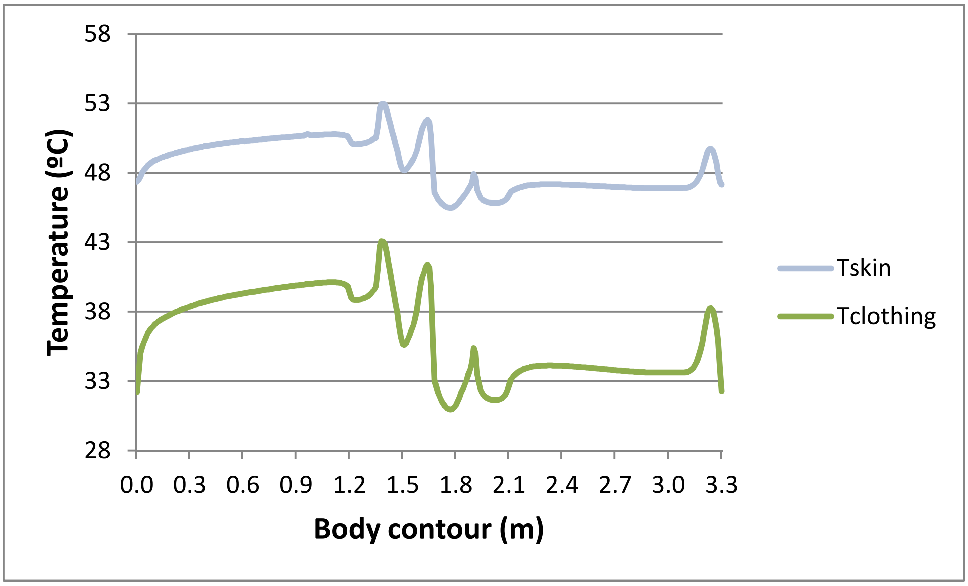

Fig 4. 55 Tskin vs Tclothing case 18 (ºC)

CASE 19

Regime	Clothing	Activity
Cooling	1.53 clo	Sedentary activity: 1.2 met

Air temperature:

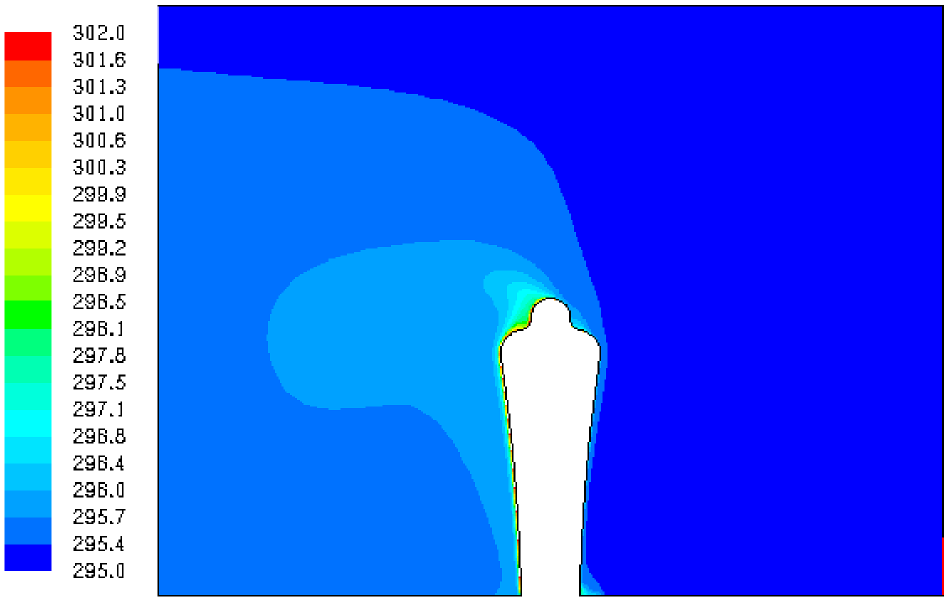

Fig 4. 56 Air temperature case 19 (K)

Velocity vectors:

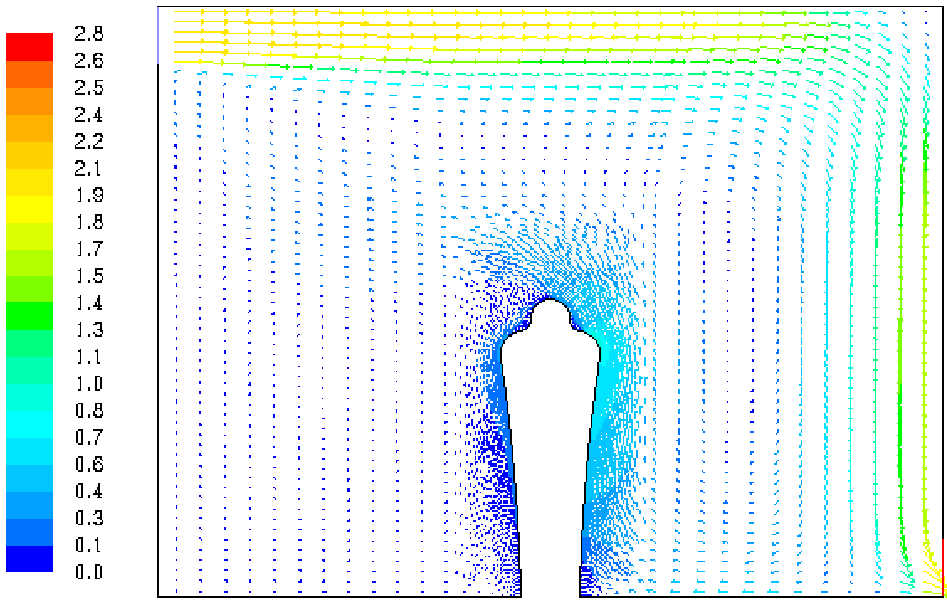

Fig 4. 57 Velocity vectors case 19 (m/s)

Comparison T_{skin} -$T_{clothing}$

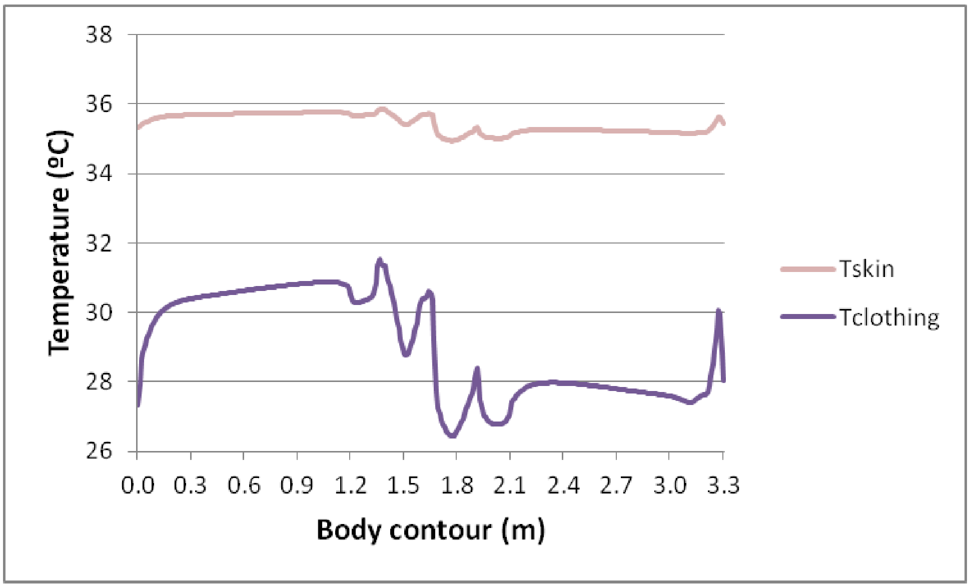

Fig 4. 58 Tskin vs Tclothing case 19 (ºC)

CASE 20

Regime	Clothing	Activity
Cooling	1.53 clo	Medium activity: 2 met

Air temperature:

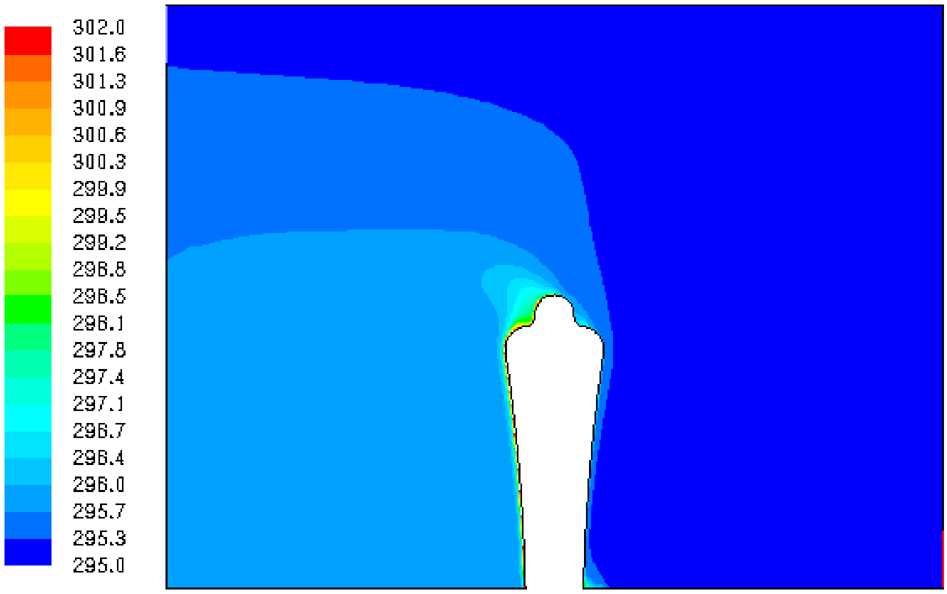

Fig 4. 59 Air temperature case 20 (K)

Velocity vectors:

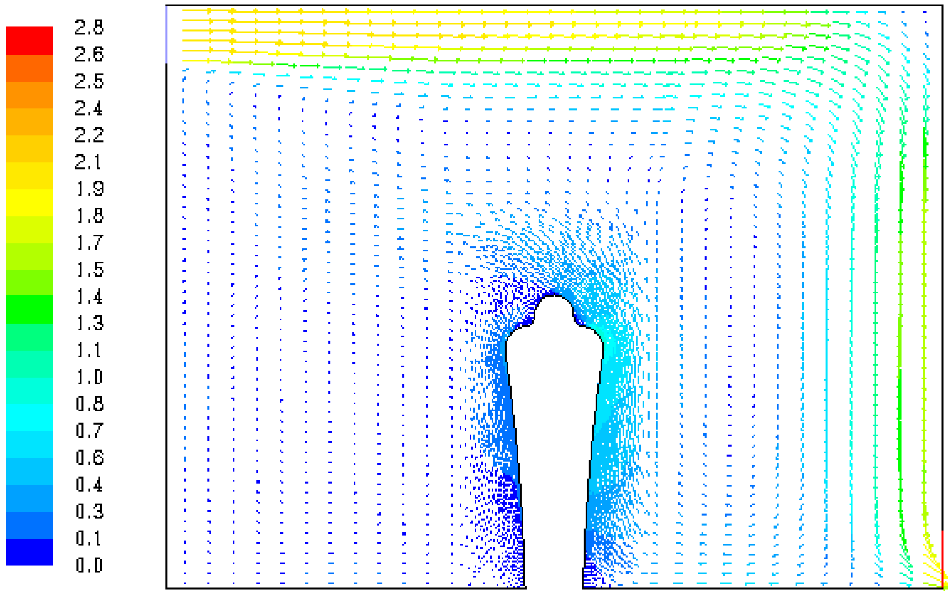

Fig 4. 60 Velocity vectors case 20 (m/s)

Comparison T_{skin} -$T_{clothing}$

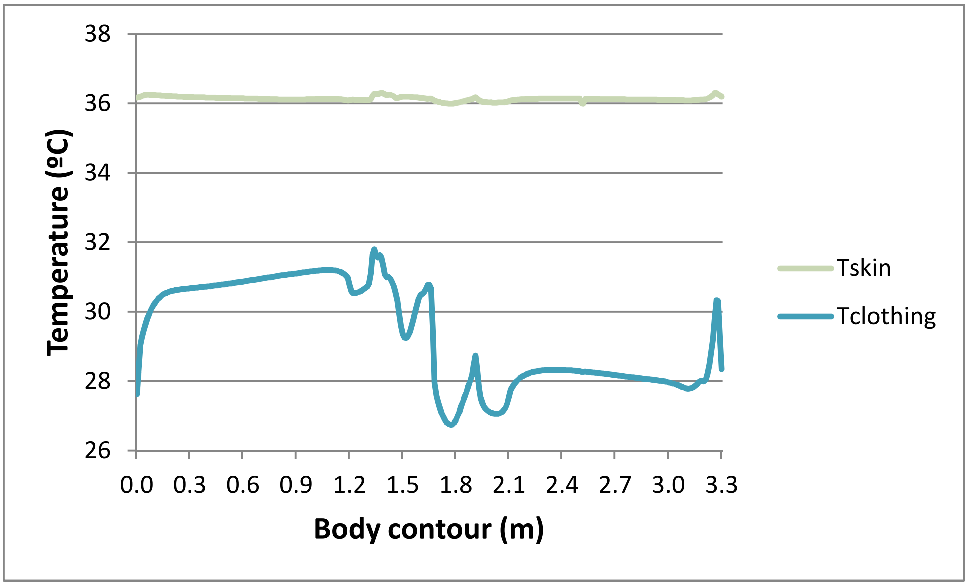

Fig 4. 61 Tskin vs Tclothing case 20 (ºC)

CASE 21

Regime	Clothing	Activity
Cooling	1.53 clo	Ironing: 3 met

Air temperature:

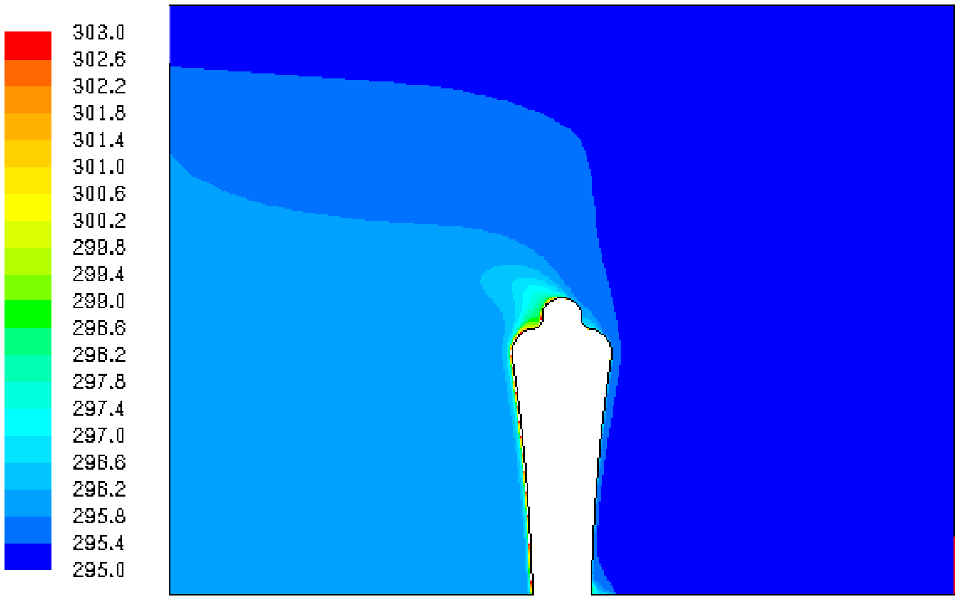

Fig 4. 62 Air temperature case 21 (K)

Velocity vectors:

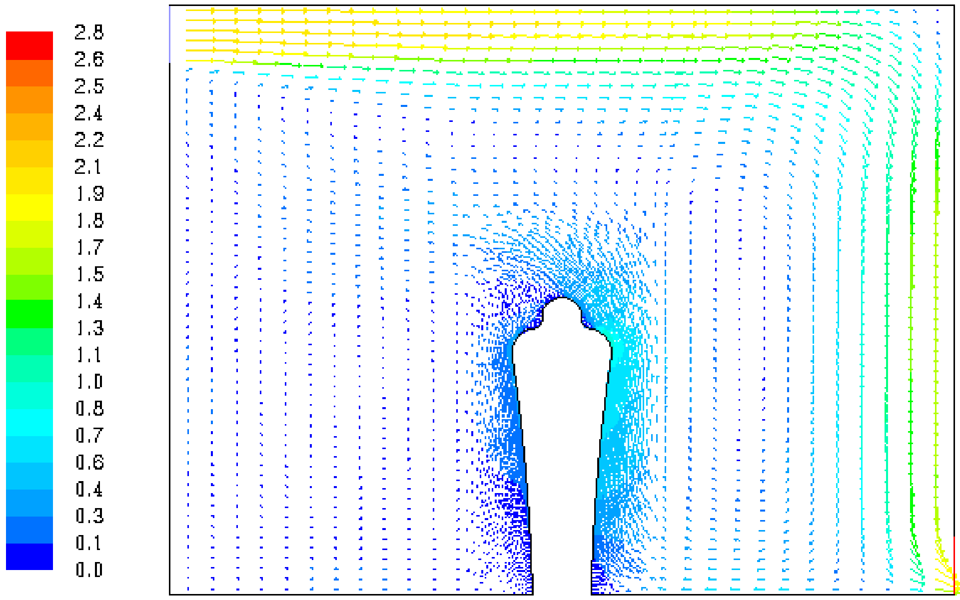

Fig 4. 63 Velocity vectors case 21 (m/s)

Comparison T_{skin} -$T_{clothing}$

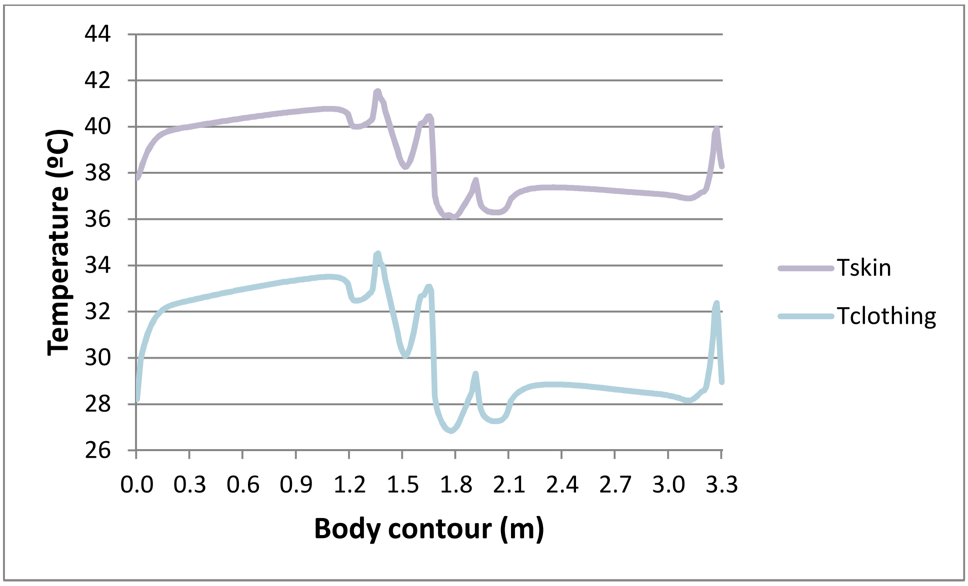

Fig 4. 64 Tskin vs Tclothing case 21 (ºC)

CASE 22

Regime	Clothing	Activity
No cooling	0.37 clo	Sedentary activity: 1.2 met

Air temperature:

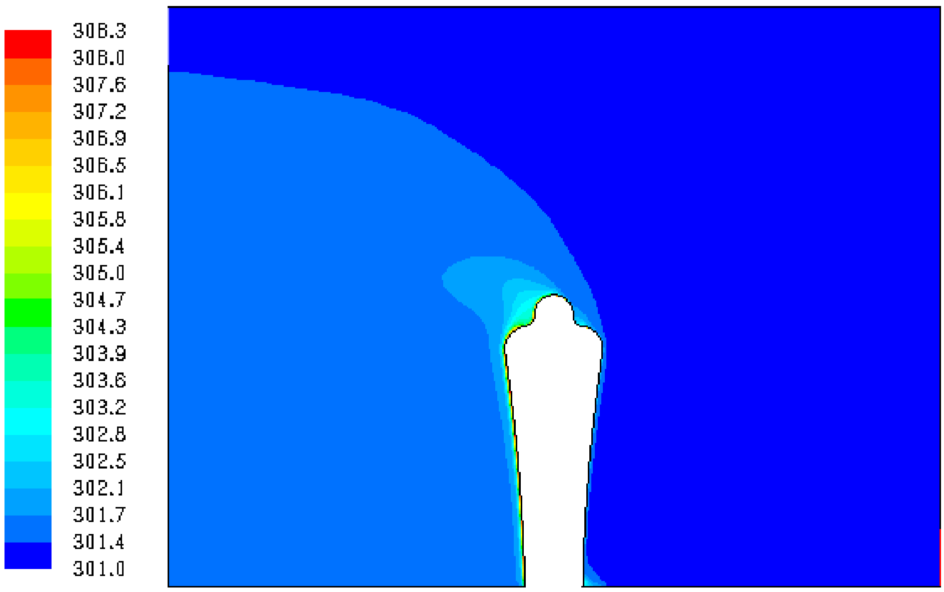

Fig 4. 65 Air temperature case 22 (K)

Velocity vectors:

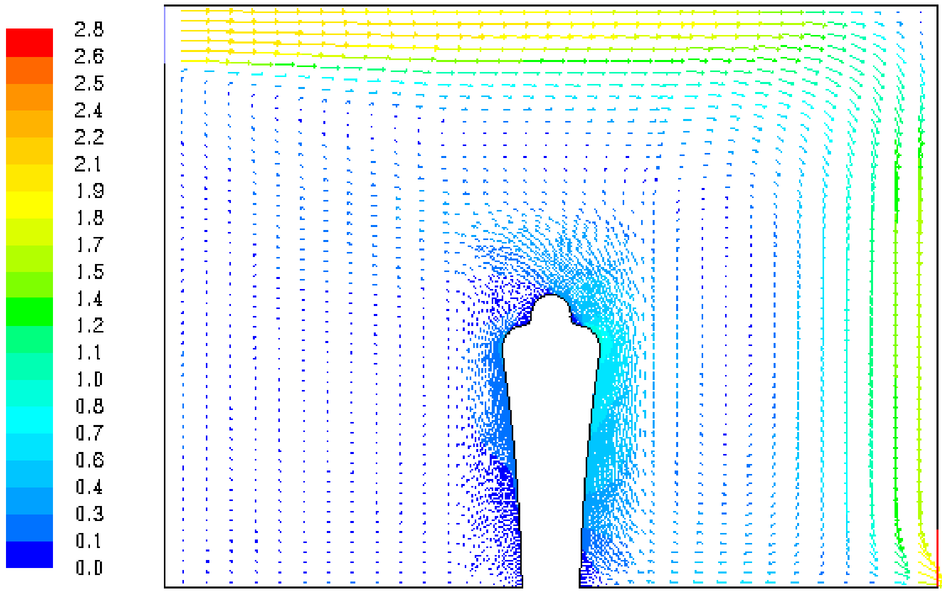

Fig 4. 66 Velocity vectors case 22 (m/s)

Comparison T_{skin} -$T_{clothing}$

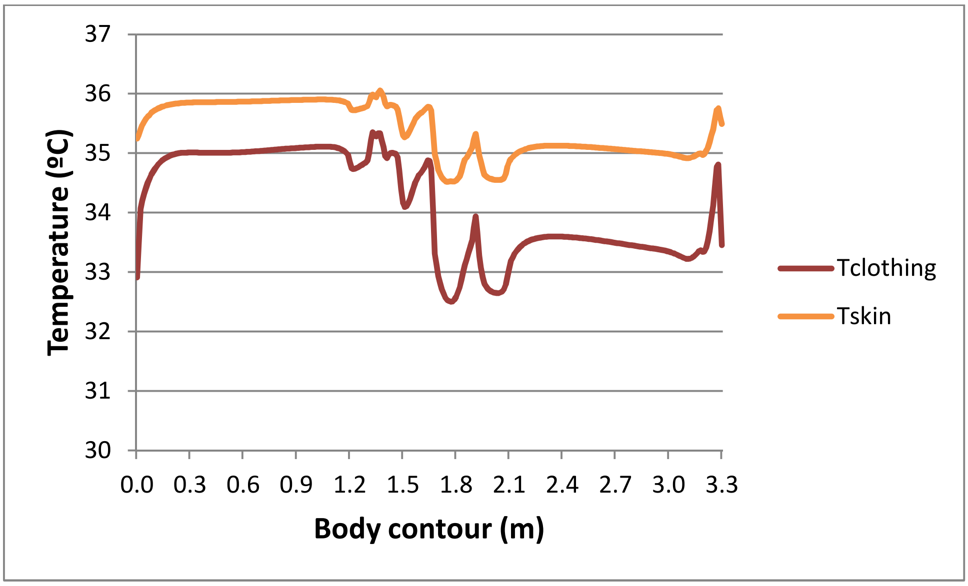

Fig 4. 67 Tskin vs Tclothing case 22 (ºC)

CASE 23

Regime	Clothing	Activity
No cooling	0.37 clo	Mediumm activity: 2 met

Air temperature:

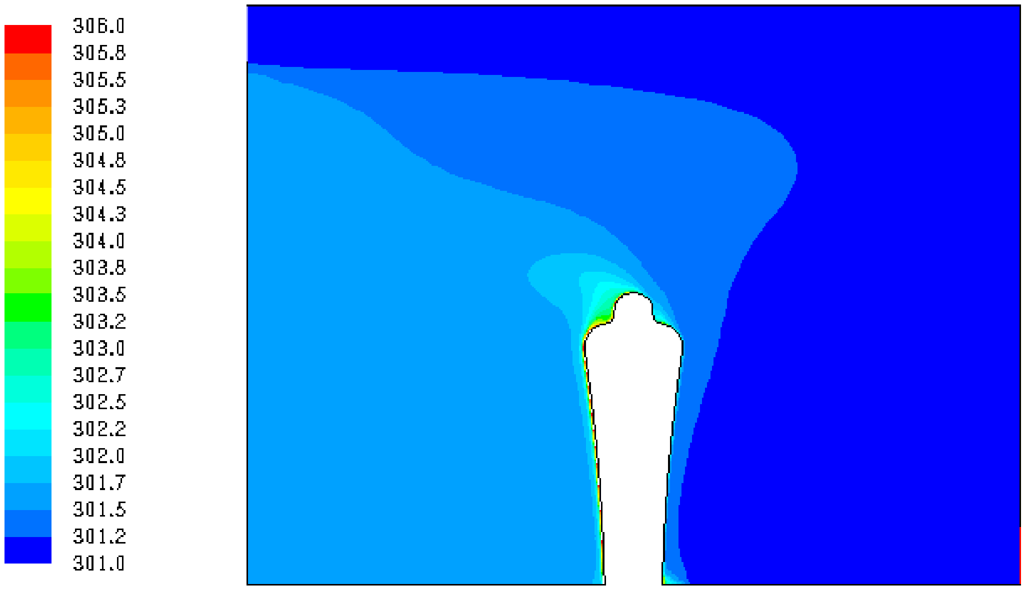

Fig 4. 68 Air temperature case 23 (K)

Velocity vectors:

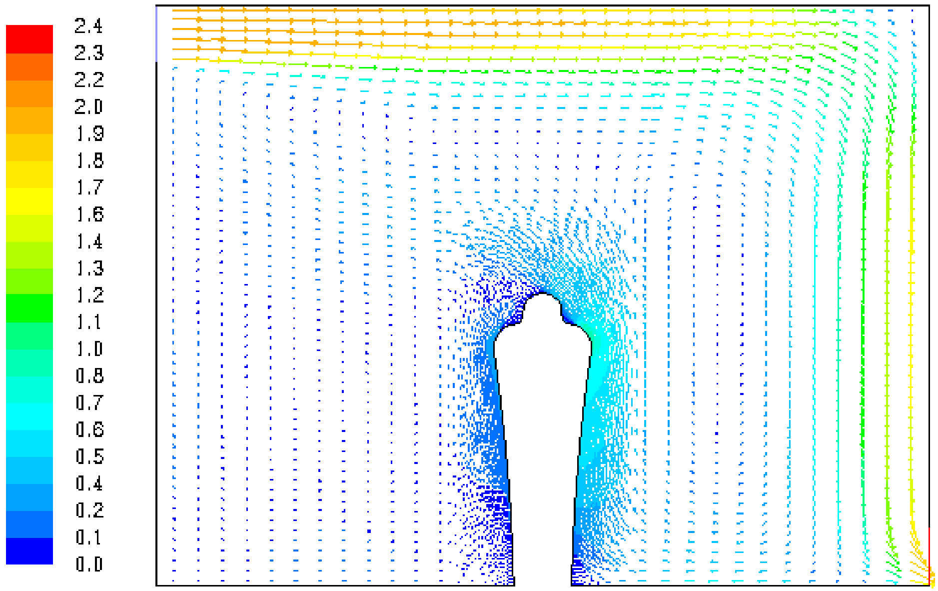

Fig 4. 69 Velocity vectors case 23 (m/s)

Comparison T_{skin} -$T_{clothing}$

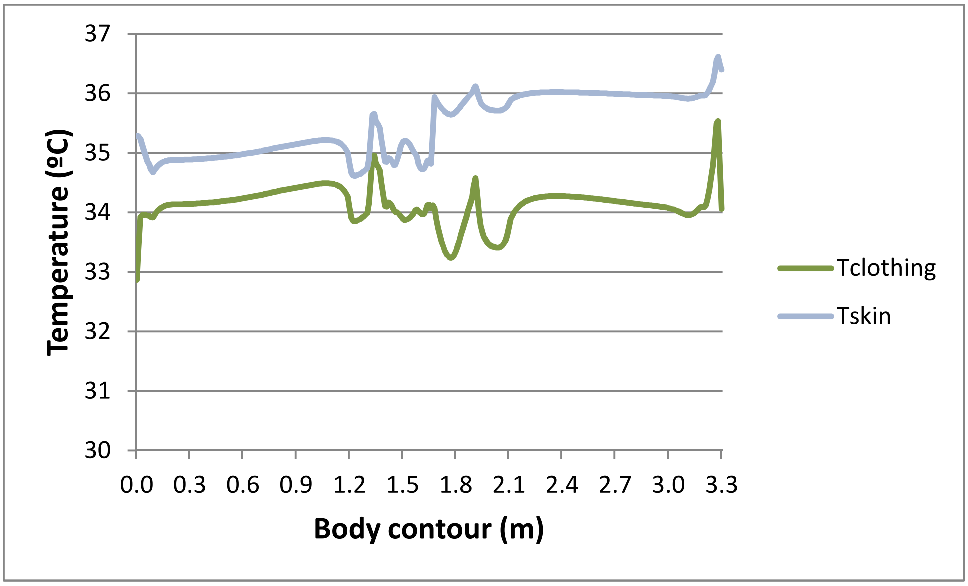

Fig 4. 70 Tskin vs Tclothing case 23 (ºC)

CASE 24

Regime	Clothing	Activity
No cooling	0.37 clo	Ironing: 3 met

Air temperature:

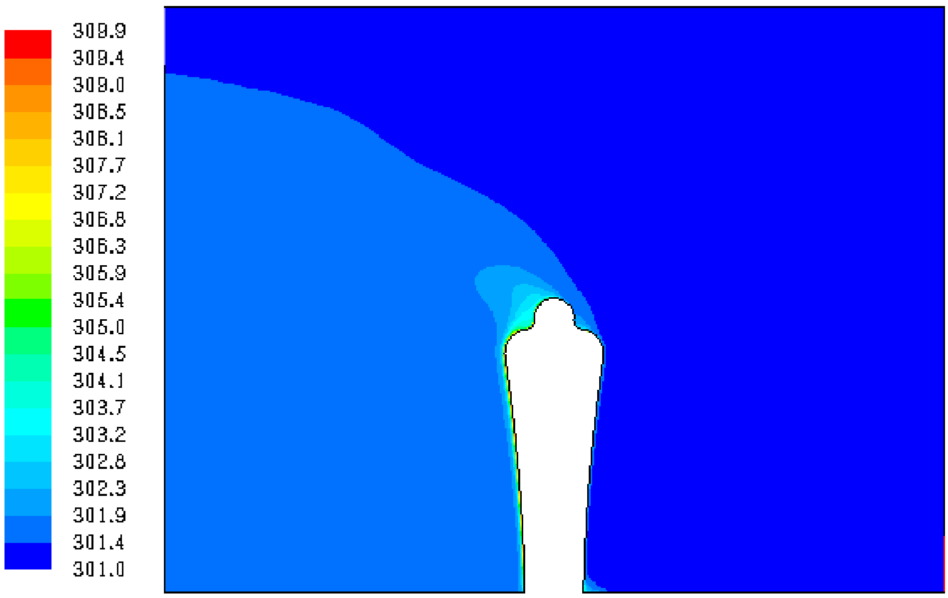

Fig 4. 71 Air temperature case 24 (K)

Velocity vectors:

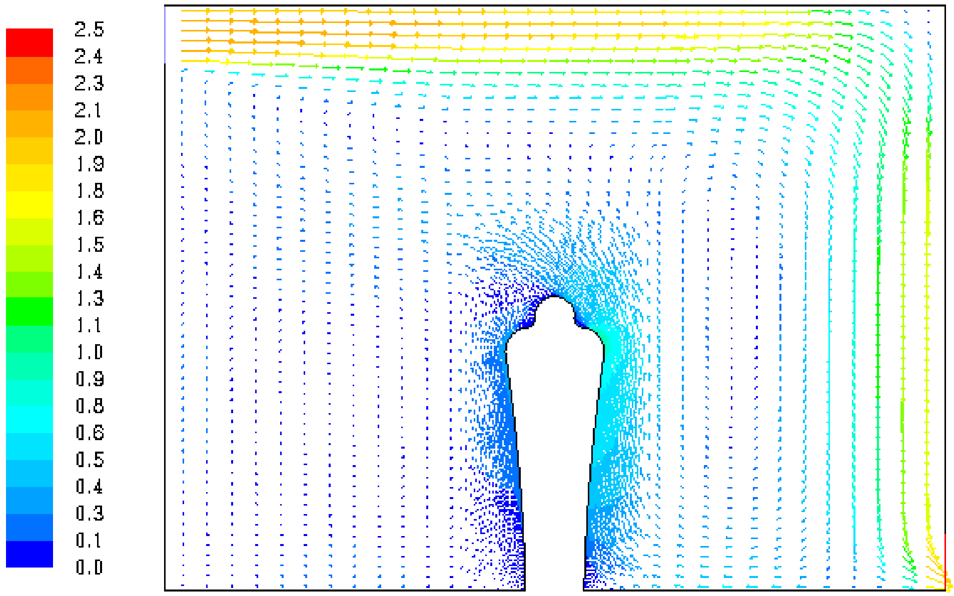

Fig 4. 72 Velocity vectors case 24 (m/s)

Comparison T_{skin} -$T_{clothing}$

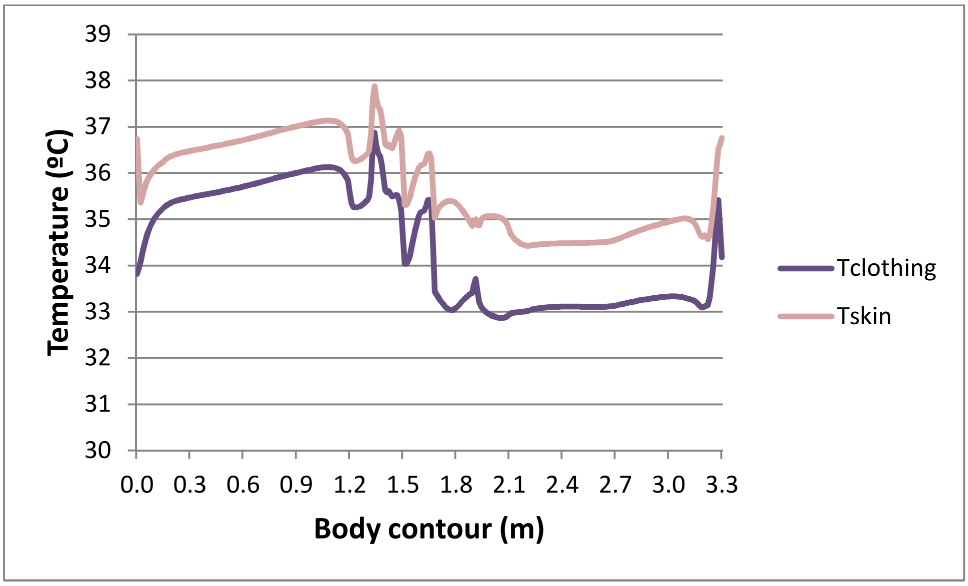

Fig 4. 73 Tskin vs Tclothing case 24 (ºC)

CASE 25

Regime	Clothing	Activity
No cooling	0.93 clo	Sedentary activity: 1.2 met

Air temperature:

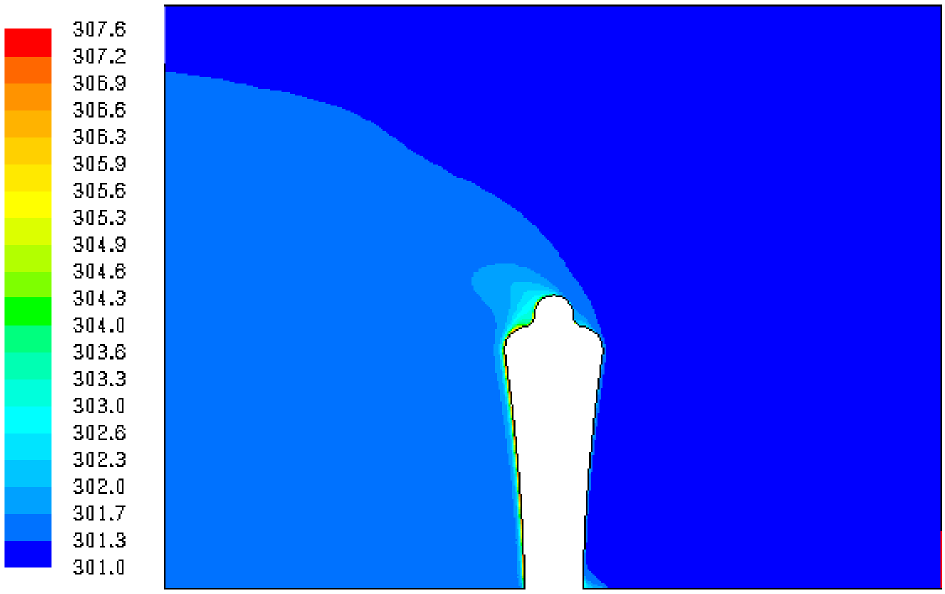

Fig 4. 74 Air temperature case 25 (K)

Velocity vectors:

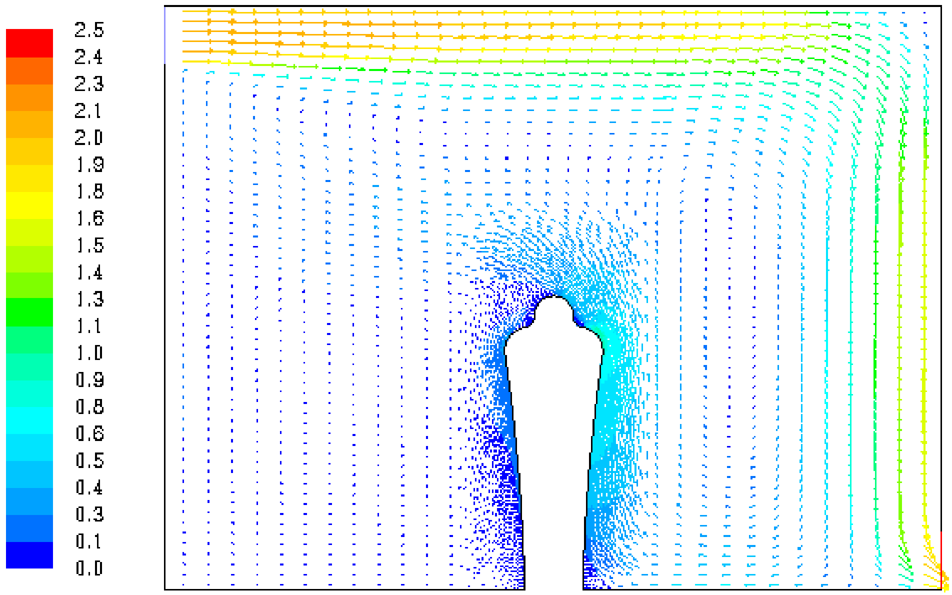

Fig 4. 75 Velocity vectors case 25 (m/s)

Comparison T_{skin} -$T_{clothing}$

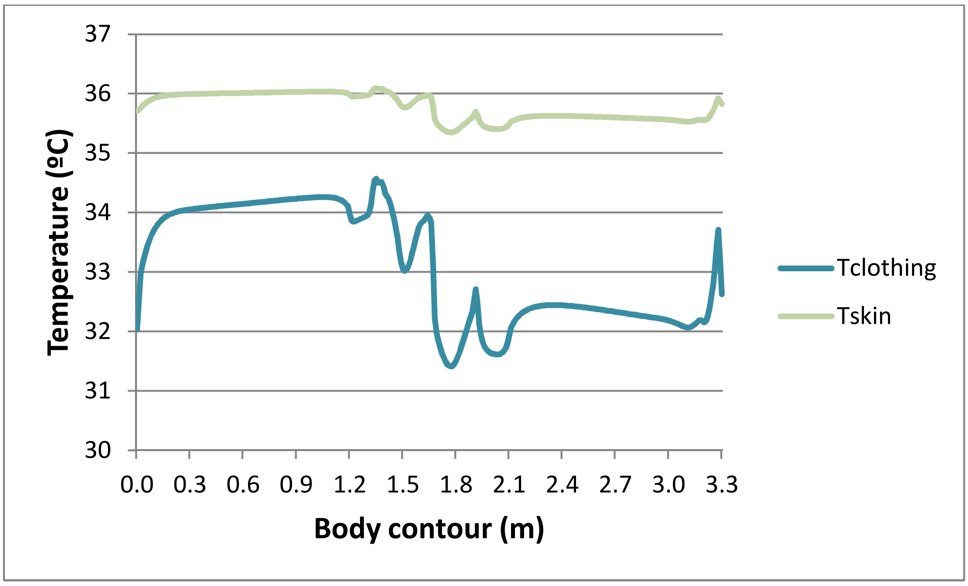

Fig 4. 76 Tskin vs Tclothing case 25 (ºC)

CASE 26

Regime	Clothing	Activity
No cooling	0.93 clo	Medium activity: 2 met

Air temperature:

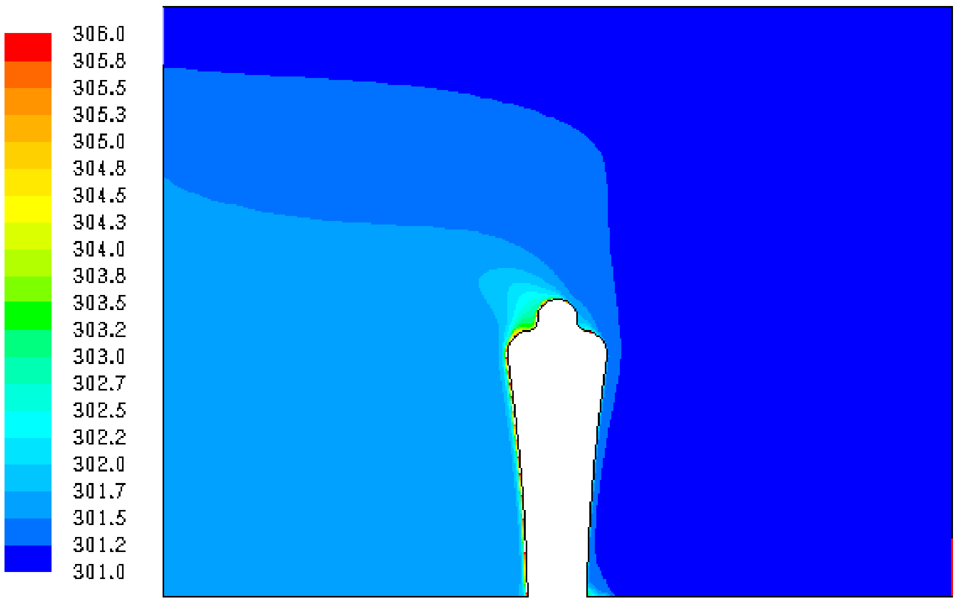

Fig 4. 77 Air temperature case 26 (K)

Velocity vectors:

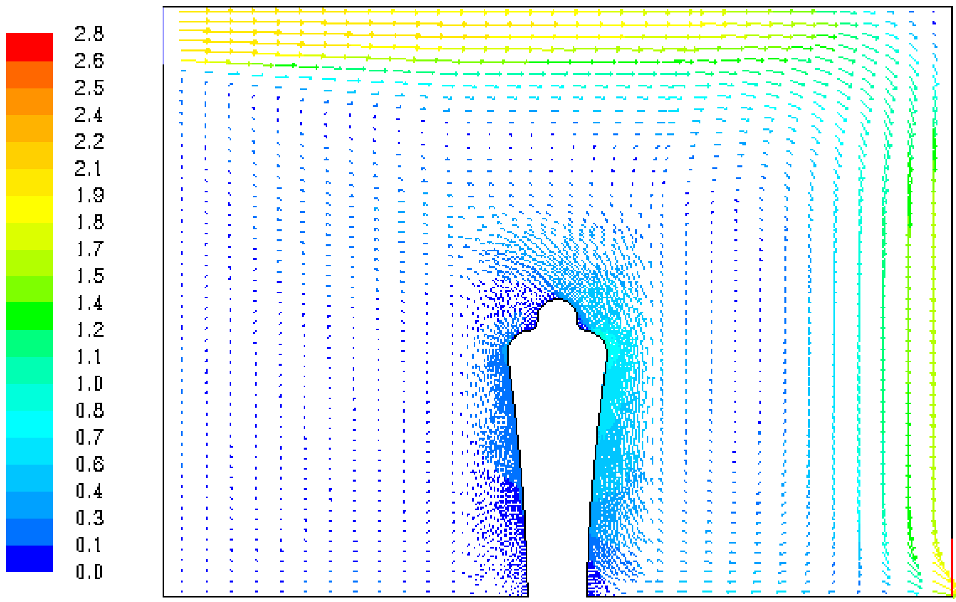

Fig 4. 78 Velocity vectors case 26 (m/s)

Comparison T_{skin} -$T_{clothing}$

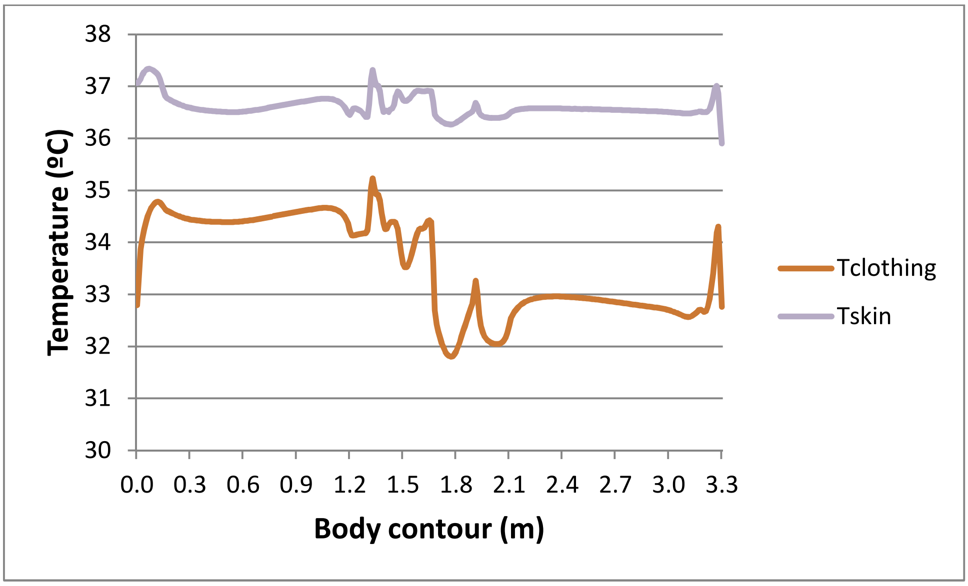

Fig 4. 79 Tskin vs Tclothing case 26 (ºC)

CASE 27

Regime	Clothing	Activity
No cooling	0.93 clo	Ironing: 3 met

Air temperature:

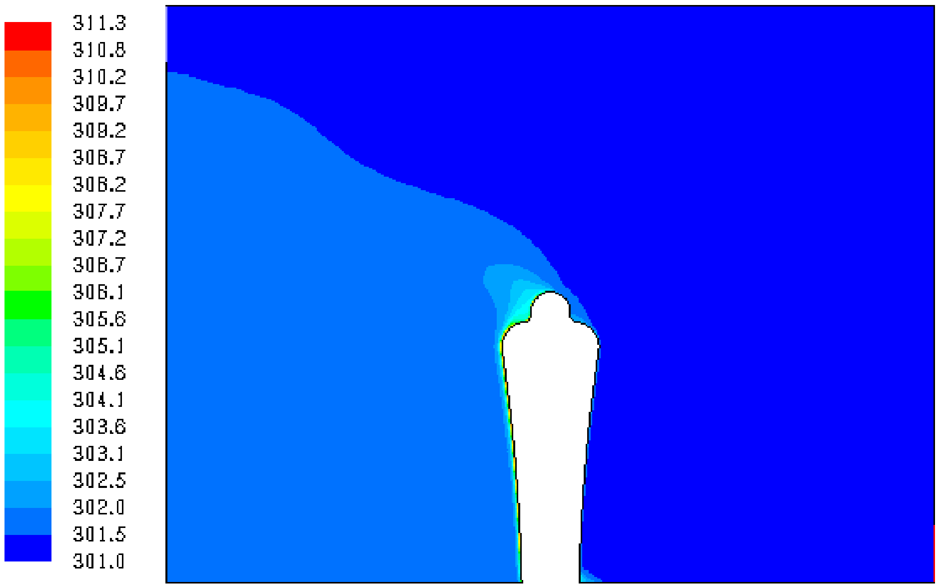

Fig 4. 80 Air temperature case 27 (K)

Velocity vectors:

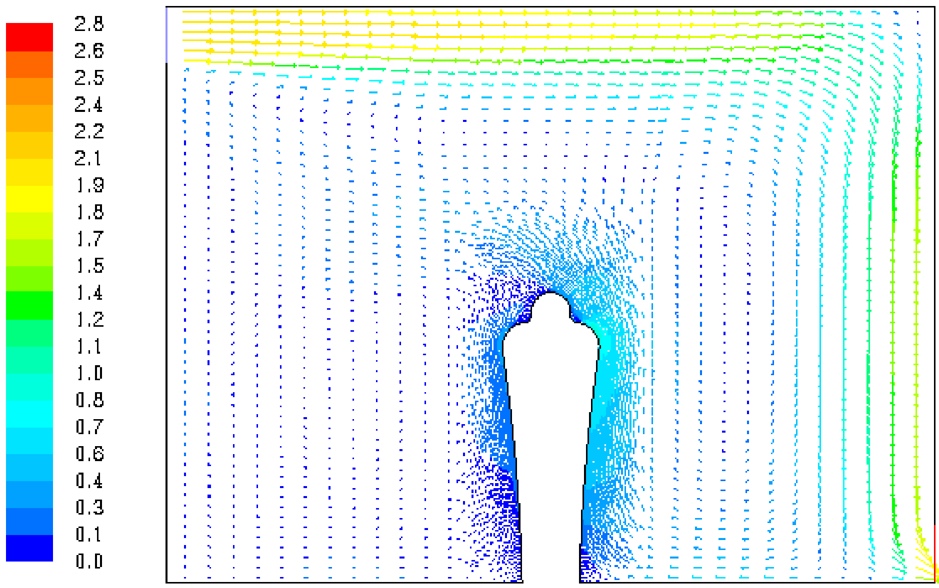

Fig 4. 81 Velocity vectors case 27 (m/s)

Comparison T_{skin} -$T_{clothing}$

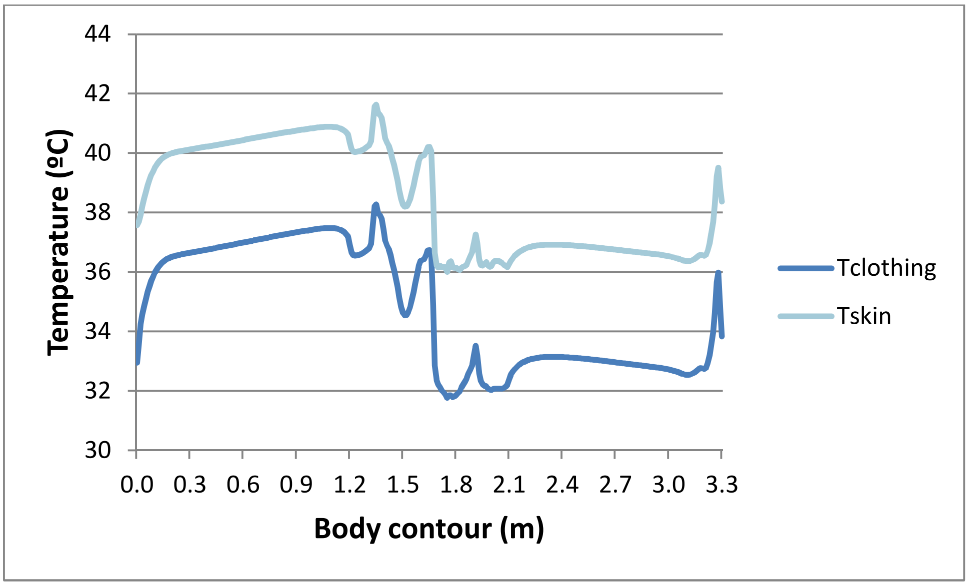

Fig 4. 82 Tskin vs Tclothing case 27 (ºC)

CASE 28

Regime	Clothing	Activity
No cooling	1.3 clo	Sedentary activity: 1.2 met

Air temperature:

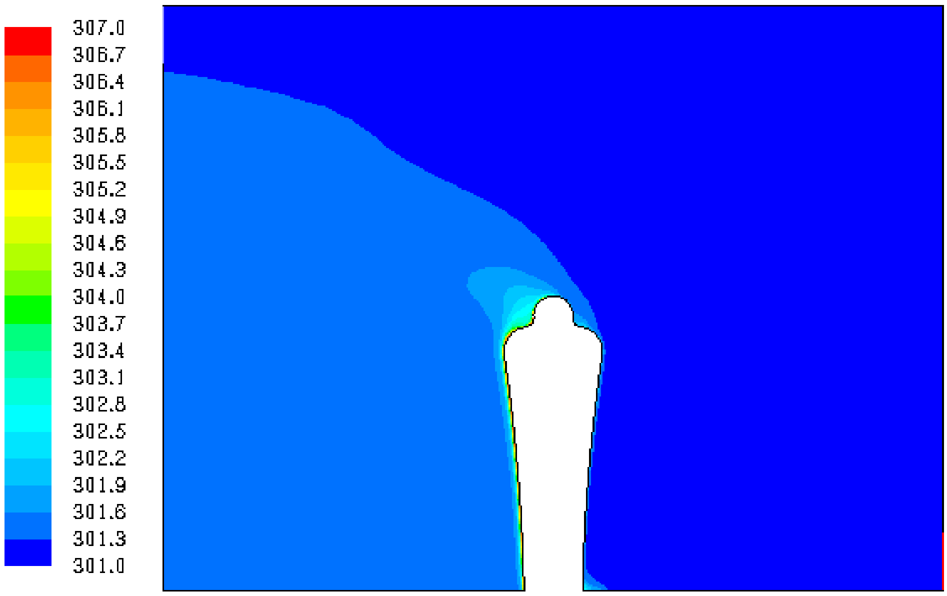

Fig 4.83 Air temperature case 28 (K)

Velocity vectors:

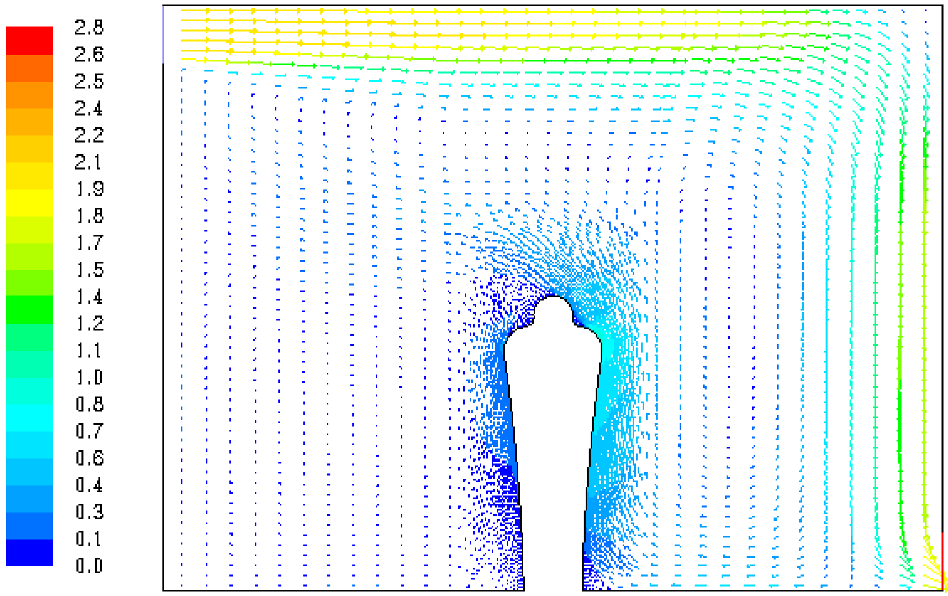

Fig 4. 84 Velocity vectors case 28 (m/s)

Comparison T_{skin} -$T_{clothing}$

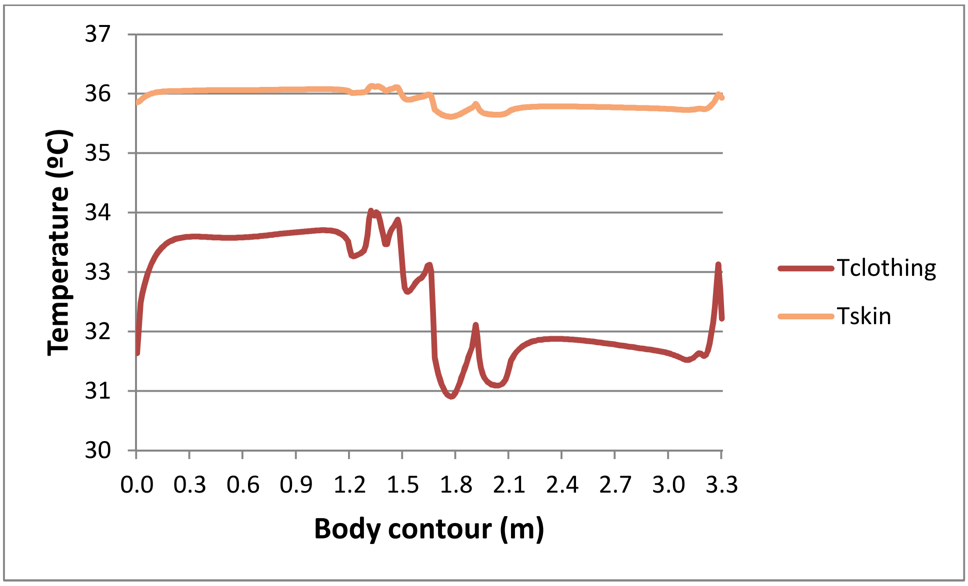

Fig 4. 85 Tskin vs Tclothing case 28 (ºC)

CASE 29

Regime	Clothing	Activity
No cooling	1.3 clo	Medium activity:2 met

Air temperature:

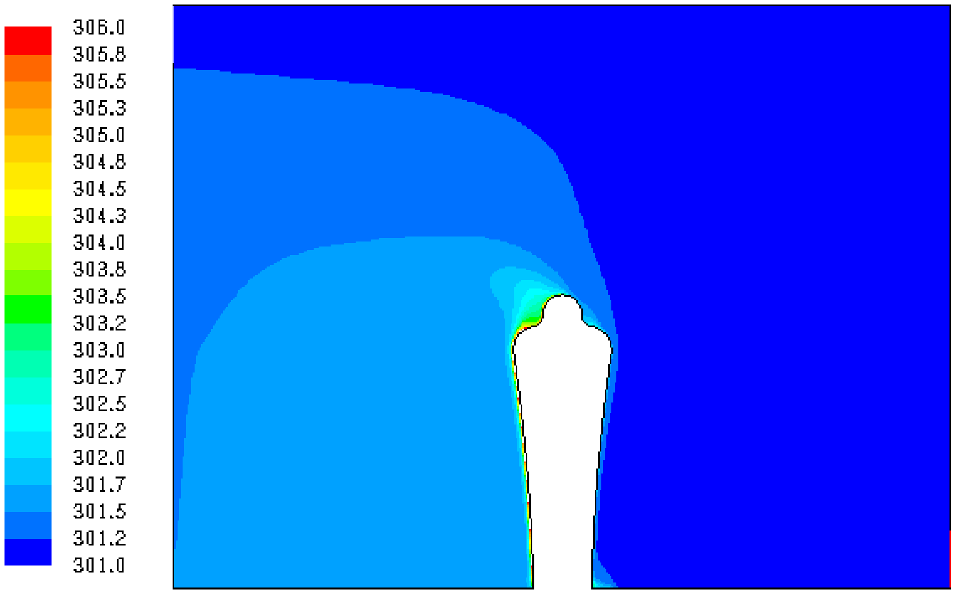

Fig 4. 86 Air temperature case 29 (K)

Velocity vectors:

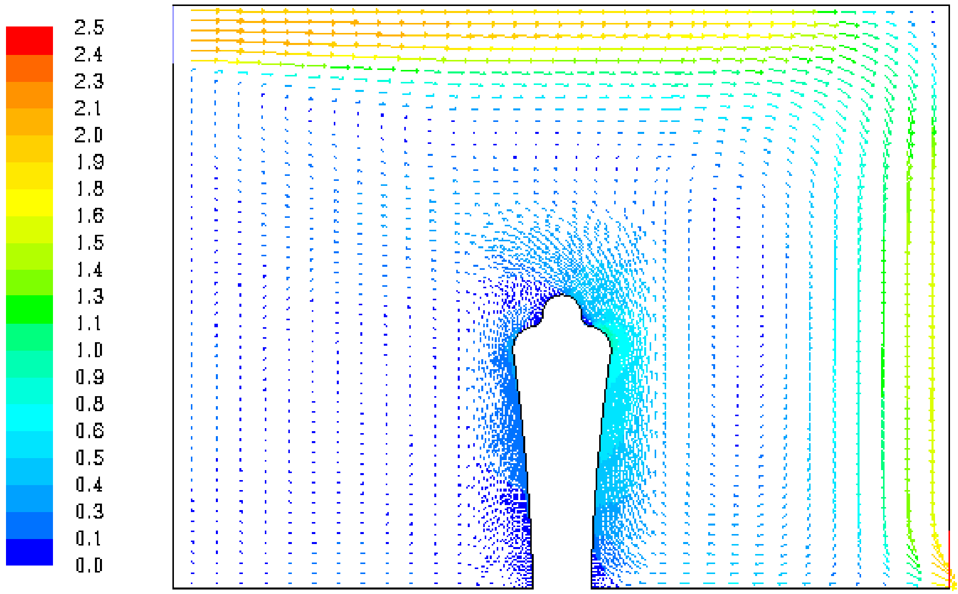

Fig 4. 87 Velocity vectors case 29 (m/s)

Comparison T_{skin} -$T_{clothing}$

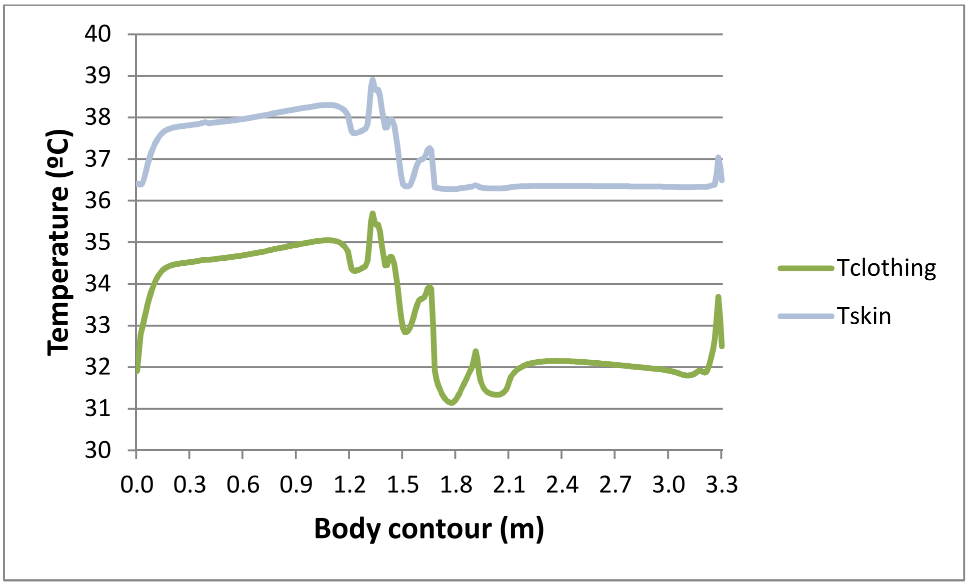

Fig 4. 88 Tskin vs Tclothing case 29 (ºC)

CASE 30

Regime	Clothing	Activity
No cooling	1.3 clo	Ironing: 3 met

Air temperature:

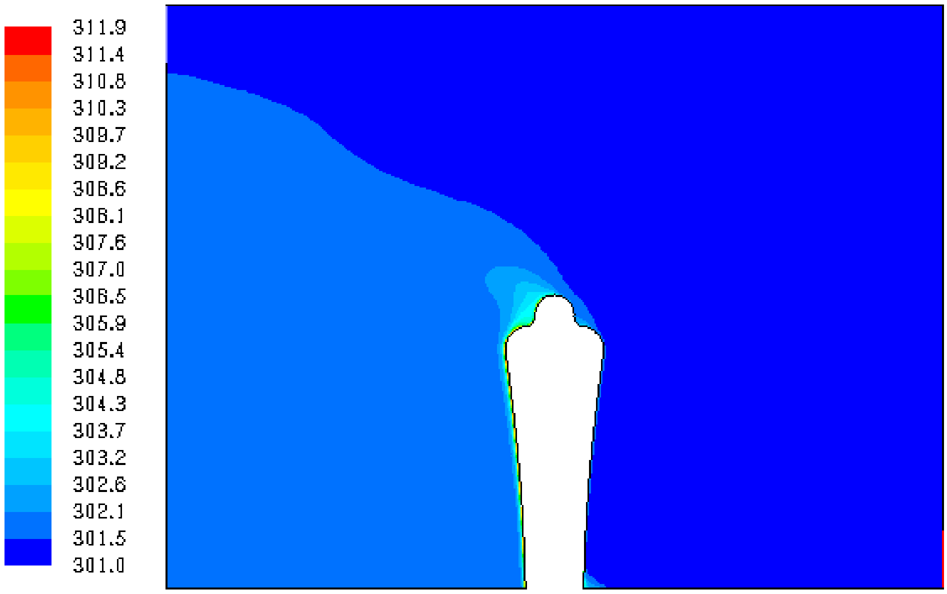

Fig 4. 89 Air temperature case 30 (K)

Velocity vectors:

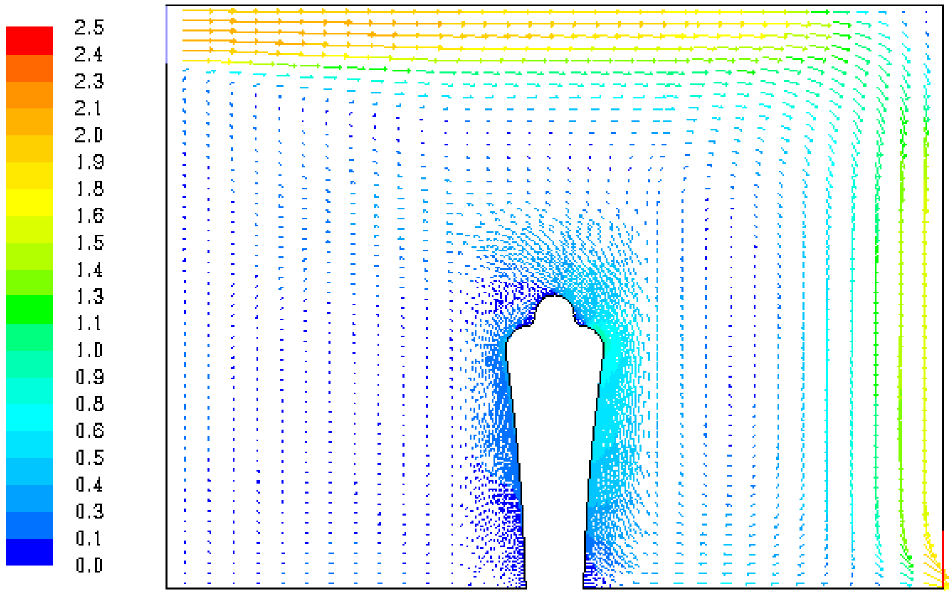

Fig 4. 90 Velocity vectors case 30 (m/s)

Comparison T_{skin} -$T_{clothing}$

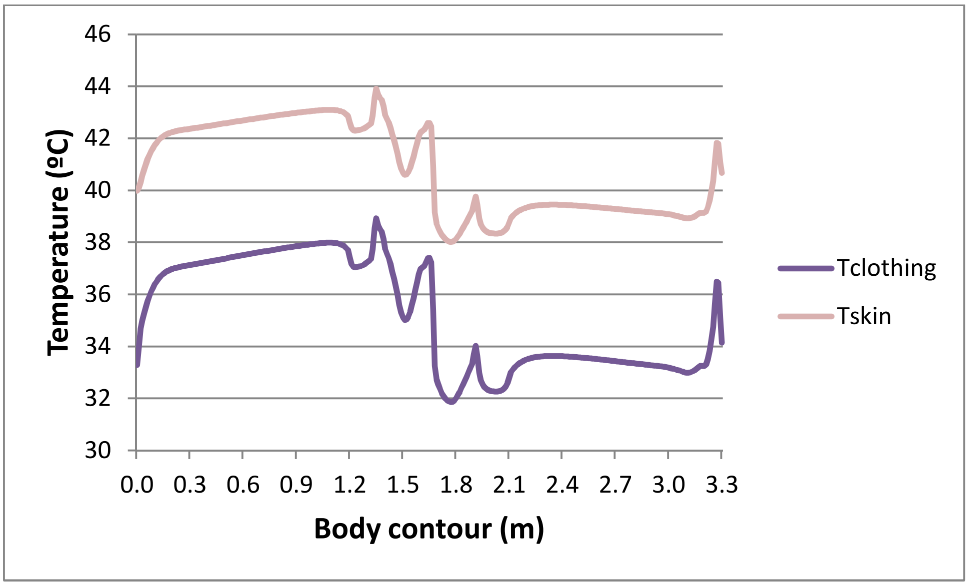

Fig 4. 91 Tskin vs Tclothing case 30 (ºC)

5. COMPARISONS AND ANALYSIS

5.1 INTRODUCTION

In this section I'm going present graphics to compare three parameters of the different cases. Firstly the analysis of the temperature of the skin, then the temperature of the clothing and to end the analysis of the heat fluxes. Within each variable I have separated the cases with the same value of clo and the same activity in order to obtain some conclusions that allow me how is the behavior of the body in different situations.

5.2 TEMPERATURE OF THE SKIN.COOLING CASE

This is the parameter which measures the temperature of the skin of the manikin which is in direct contact with the clothes.

5.2.1 Skin temperature according to the clothing

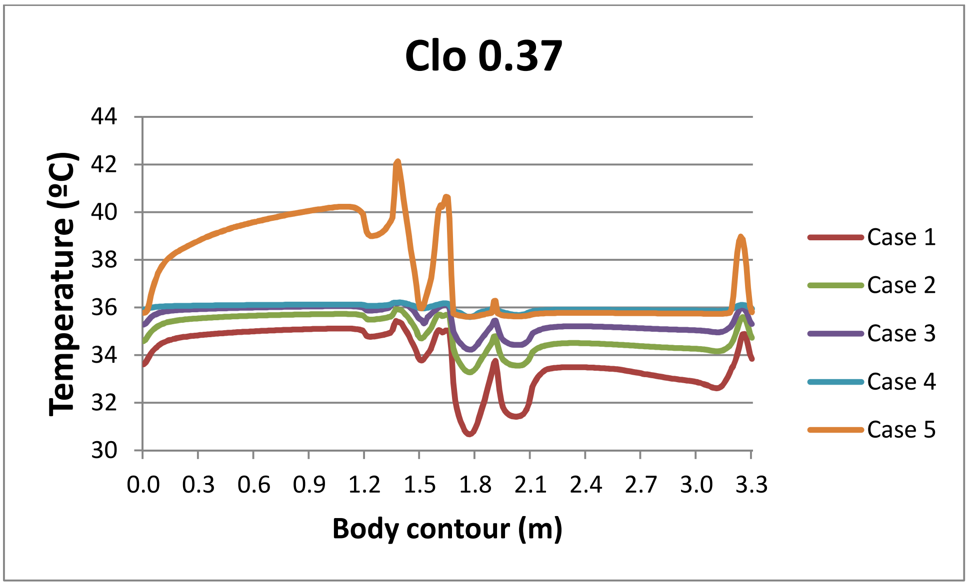

Fig 5. 1 Skin temperature in the cooling cases with 0.37 clo

The cases with low and medium activity reach temperatures of the skin very similar in the side which is more exposed to the air flow. In the right side (if you look from the front) the differences of the temperatures among the low and medium cases are bigger. However the difference in respect of the case which has an activity of 6 met is smaller in that side than in the other.

Specially attract the attention the case with h higher activity (case 6) because in the side which is exposed to the flow reaches high skin temperatures but in the other the temperature is almost the same than in the case 4 and is more stable.

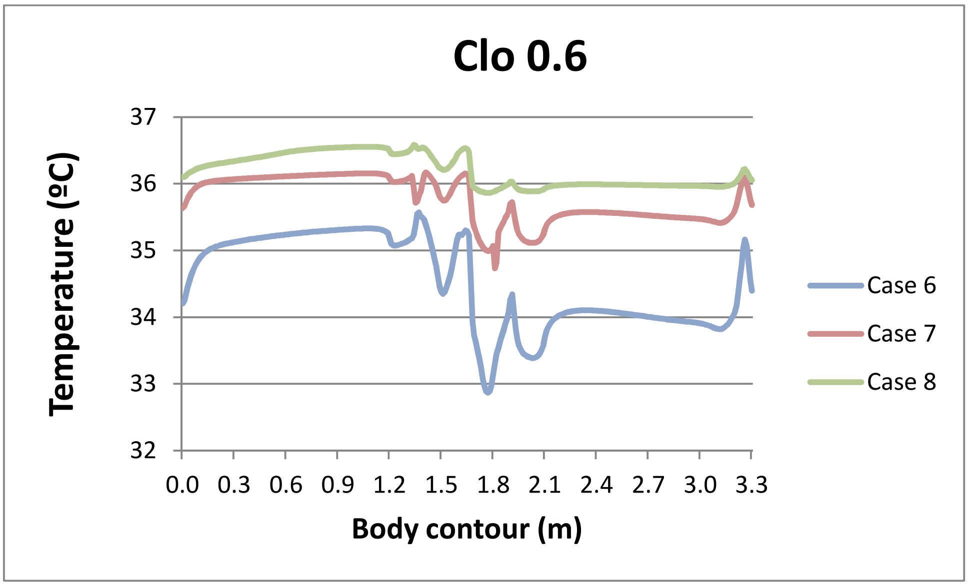

Fig 5. 2 Skin temperature in the cooling cases with 0.60 clo

Here the most representative is the shape of the graphics, they are alike, an upward first part then a zone with ups and downs (more clear in case 6) in the part of the head. The last part is more or less uniform until at the end there is a recovery of the temperature, more clear also in case 6

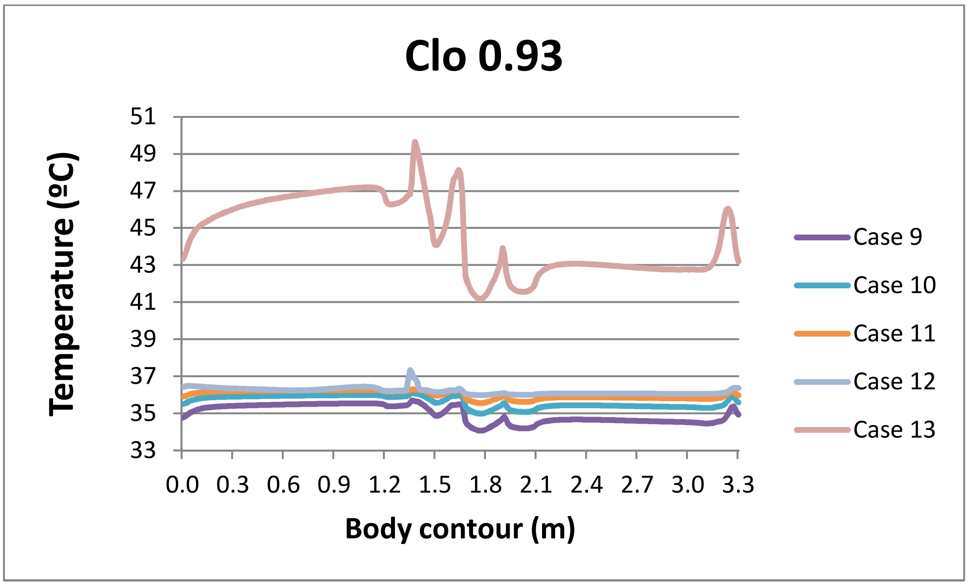

Fig 5. 3 Skin temperature in the cooling cases with 0.93 clo

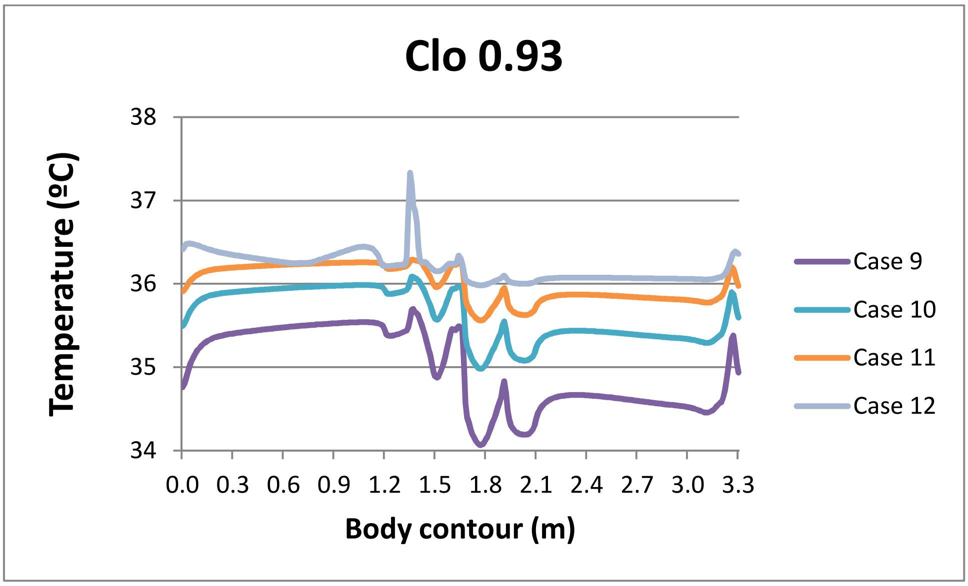

Fig 5. 4 Detail of the skin temperature in some cooling cases with 0.93 clo (ºC)

In this graphic we can see the big difference among the cases with low/medium activity and the high activity case which reaches excessive temperatures because is too much clothes to be running.

The temperatures of the other four cases are between 34ºC and 37ºC with a graphic which has the same tendency. At the end of the contour (the right foot) there again a punctual recovery of the temperature probably because in that point the air is almost still and doesn't evacuate the heat.

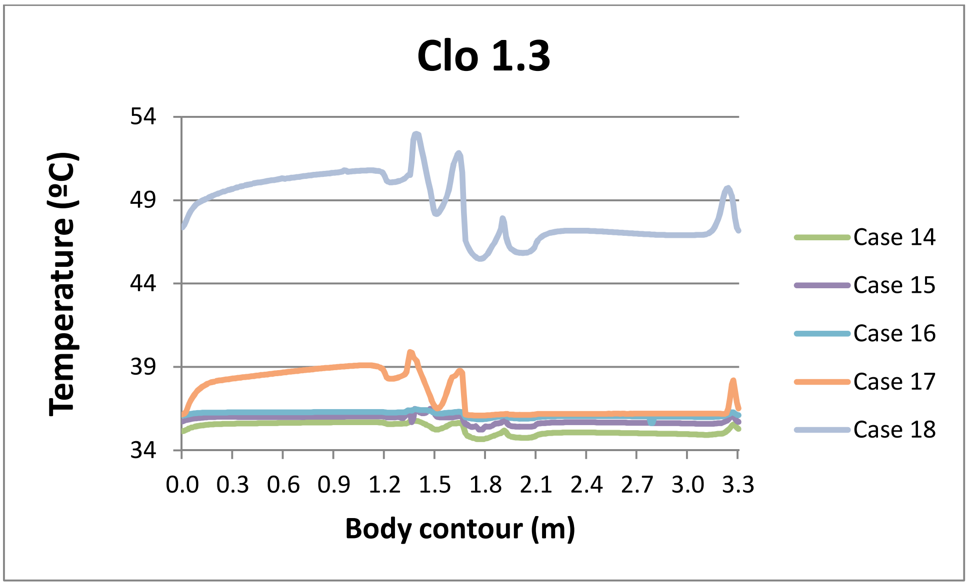

Fig 5. 5 Skin temperature in the cooling cases with 1.3 clo (ºC)

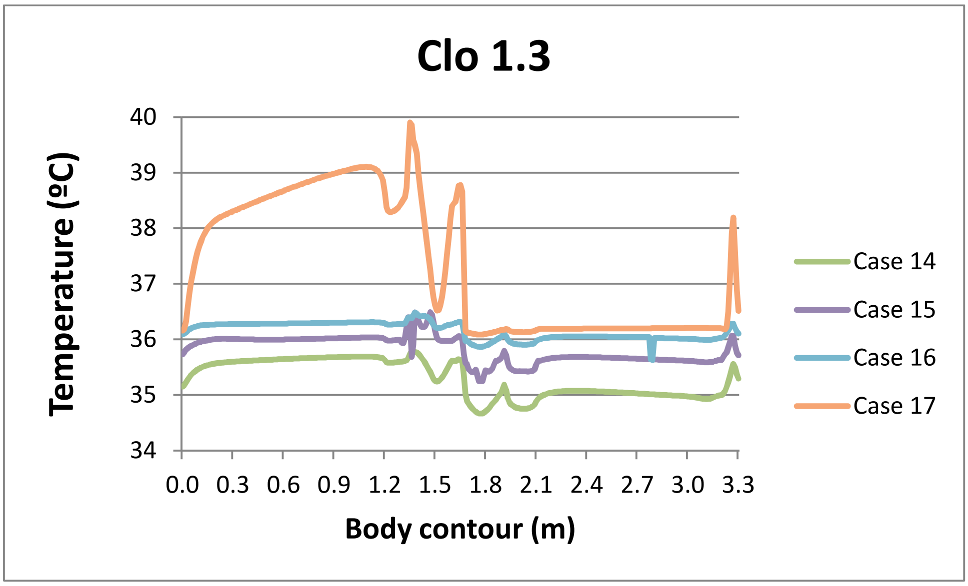

Fig 5. 5b Detail of the skin temperature in some cooling cases with 1.3 clo (ºC)

In this case we can see again the big difference between low/medium cases and the case number 18.The values of the temperature in this case is out of proportion but the case 17 starts reaching high values due to is not normal to iron with this amount of clothes

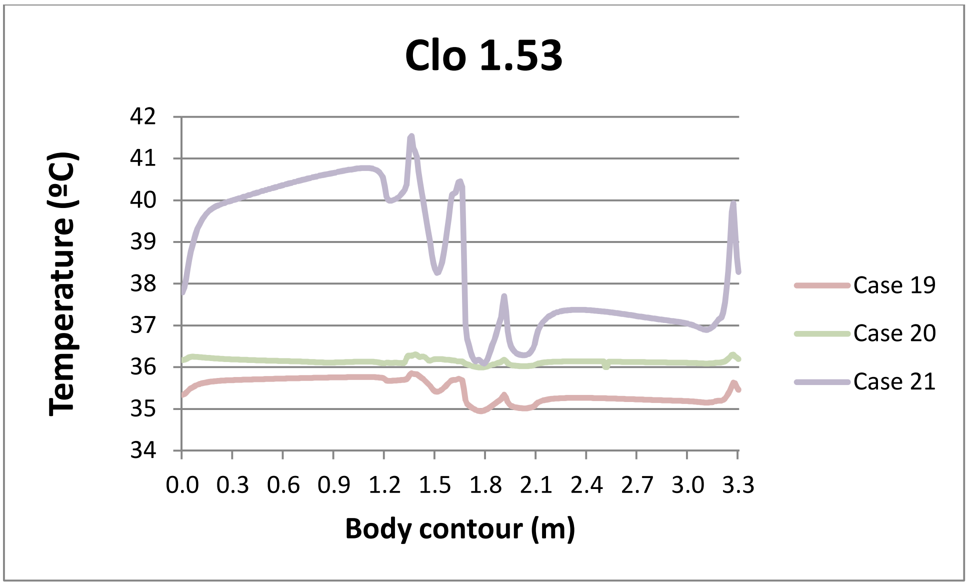

Fig 5. 6 Skin temperature in the cooling cases with 1.53 clo (ºC)

This graphic show that the case 21 has changing values, it looks unstable and can be because the model doesn't work quite right
However the other two cases are very stables and practically uniforms even in the head part. In this case is unviable to iron with this high value of clothing

In general we can say that the skin temperature increase as the activity is higher for the cases with the same value of clothing

When the activity is running, aerobic we reach very high temperatures that have no sense because they are mortal due to I analyze unreal situations, you can't go to make sport with a big quantity of clothes.
As the value of clothing increase the temperatures are higher and the difference in relation to the cases with the same clo is clearer.

The temperature of the left side of the body is higher than in the right part because is more exposed to the air which comes in from the supply entrance and has a temperature of 22ºC and this is the reason because of it is more affected. In the right side there are less movement of air so theoretically the temperature should be higher because the evaporation is lower but this part of the body is not directly exposed to the heat source and doesn't be heated as much as the left side .The right part lost much hot by convection because the difference of the temperature among the body and the surroundings is bigger than in the other side.

The head area has more unstable temperatures with continuous rises and falls. In this part is easy to reach the higher and the lower values in each case. The reason for this is that through the head is where more heat is lost because is the more exposed part due to not have any protecting clothing of the outer

5.2.2 Skin temperature according to the activity

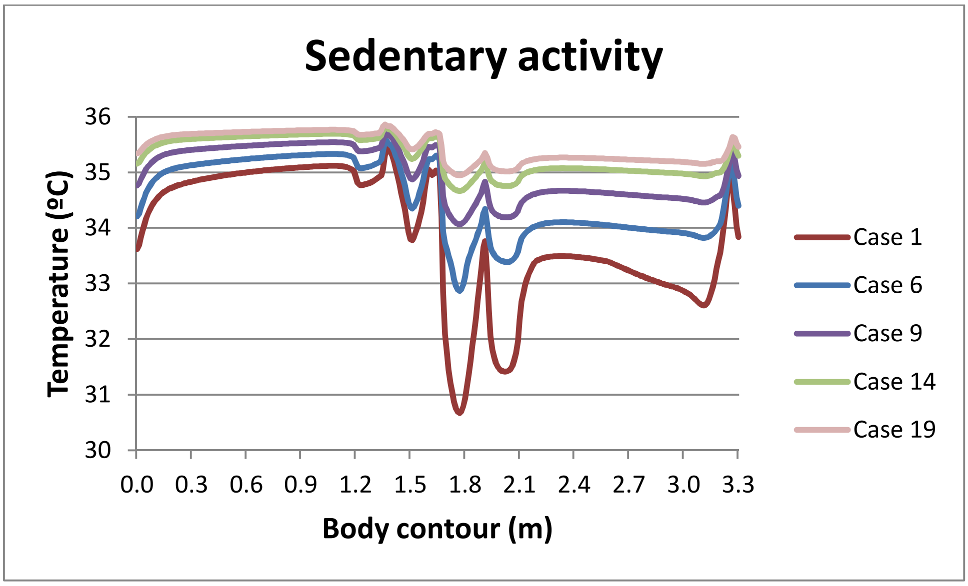

Fig 5.7 Skin temperature in the cooling cases with sedentary activity (ºC)

The graphics are very similar each other with a uniform distance among the cases , except maybe the case 1 looks the more unstable due to it is constantly up and down above all in the head zone.
The temperature values are not too much high because the activity doesn't have a high met value.
The case 19 is superimposed to the case 14 in the zone more exposed to the air flow but after reaches a slightly superior temperature.

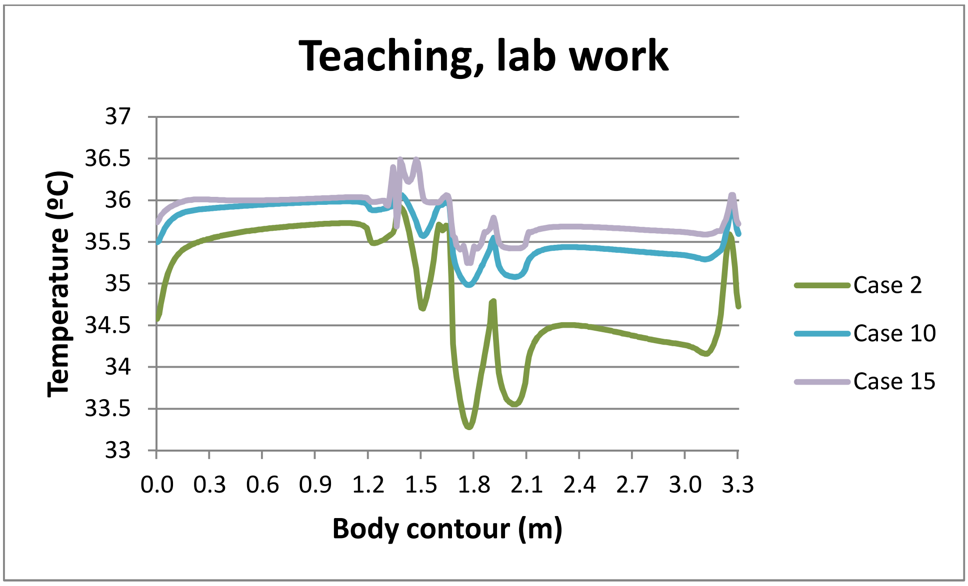

Fig 5.8 Skin temperature in the cooling cases of teaching, lab work (ºC)

In this graphic we can see that the case with low clothing is again the most unstable because if you dress scantily is easy to lose and gain heat and consequently the temperature decrease or increase because you are less insulated against the air of the surroundings. Although in some zones the case 2 shows large increases the values are almost always lower than in the case s 10 and 15.

Here again there is a superimposition of the cases 15 and 10 in the left part but then in the right part the case 15 is over because the isolation in the zone with more air affection is less effective and there is a high heat transfer due to the movement of the air, however on the other side if you wear more layers of clothes and you are not directly exposed to an air flow the difference of the skins temperatures are bigger.

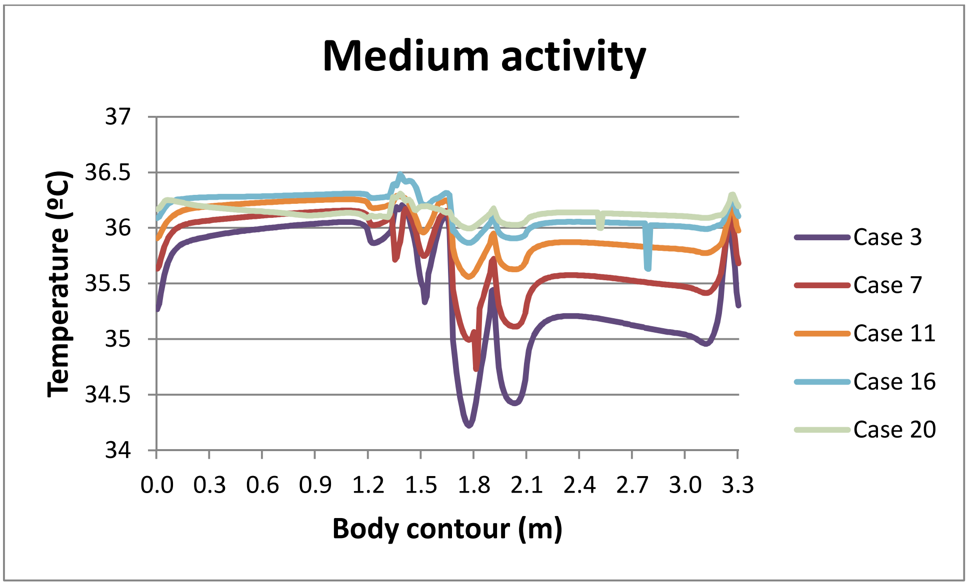

Fig 5.9 Skin temperature in the cooling cases with medium activity (ºC)

The most notable aspect of this graphics is that they have more or less the same shape except the case 20 because the temperature is around 36ºC and not even in the head zone present any irregularity. This is due to we are doing an activity which generates a lot of heat and we are dressing with too much clothes, but we are going to evacuate the heat regularly i.e. we are not going to be as affected by the air because all the layers of clothes protect us for the air of the surroundings.

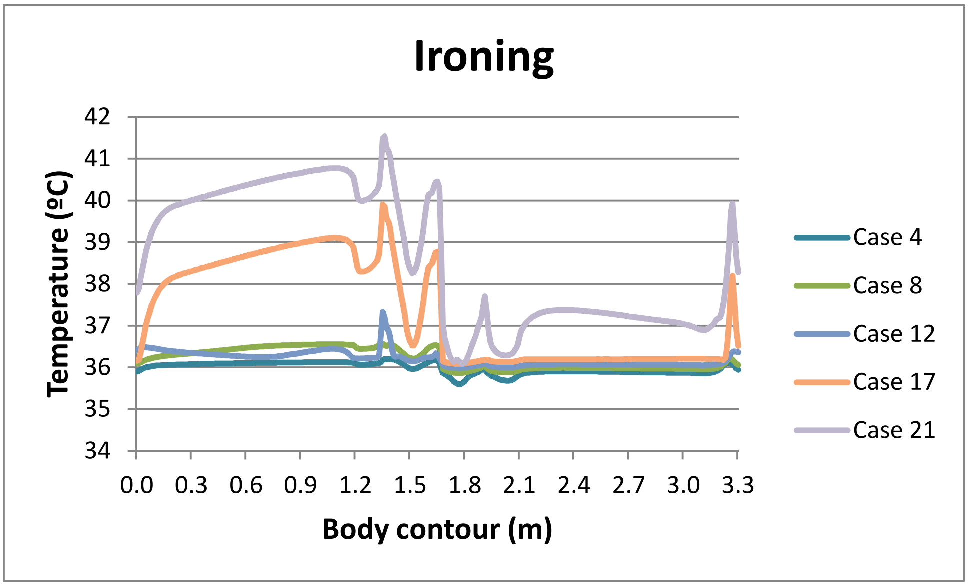

Fig 5.10 Skin temperature in the cooling cases of ironing (ºC)

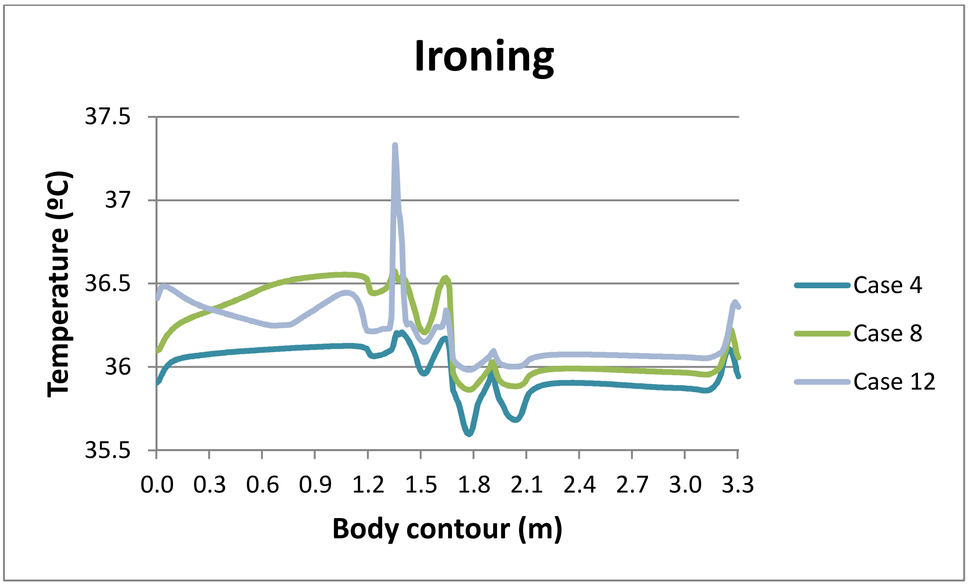

Fig 5.11 Detail of the skin temperature in some cooling cases of ironing (ºC)

Here we can see two cases which are clearly on top of the rest of the cases and they are which have the higher clo value. However the cases 4, 8, 12 the skin temperature is between 35.5ºC and 37.5ºC.

The values of the skin temperature, mostly in the left side of the body, are excessive and unreal because both cases (is most easy to see in case 21) aren't realistic,doesn't have sense to iron with too much clothes.
They are unstable cases because they have decreases and increases of the temperature constantly and however the others cases show right values, more regulars and without too much variation

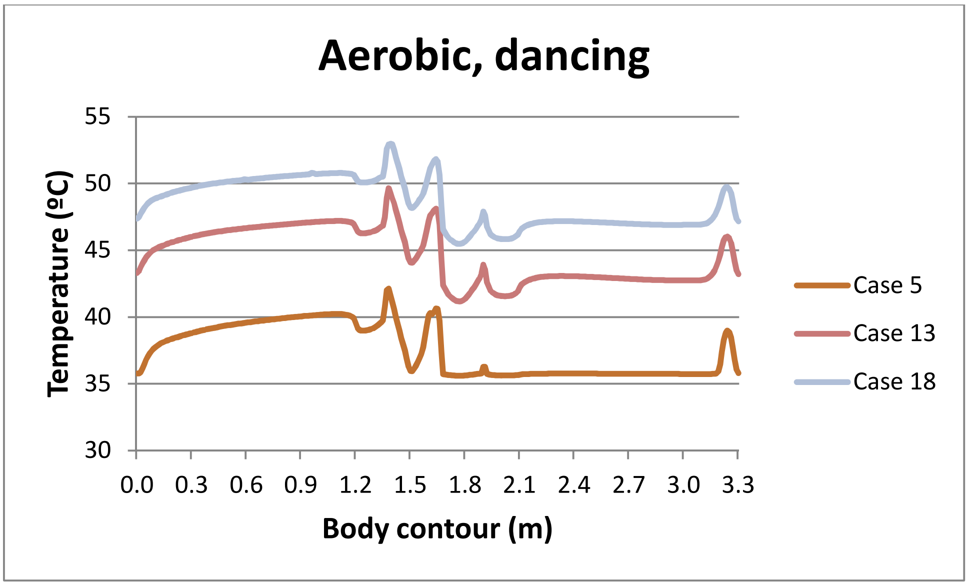

Fig 5.12 Skin temperature in the cooling cases of aerobic, dancing (ºC)

In this case all the graphics have the same tendency and shape: It rises slightly in the first part, then in the head zone there are two alterations, the last phase (right part of the model) has practically the same value except at the end (foot zone) where is a recovery because in this part the air is almost stopped and there isn't a big lost of heat by convection.

But the three cases have temperature values that aren't realistic because these are cases in which the person is doing an sport (an important effort) but the dressing is not the most suitable because with these temperatures the person will died.
The best way of dressing when you are going to do sport is to wear light and breathable clothes in order to allow the body be refrigerated. Good clothing can be clothes with a value of around 0.28-0.30 clo i.e. a t-shirt with short sleeves, a short sport trousers and slight trainers.

Also is necessary to say that the computational human body model I have used to make this project is in his limit with these values of clothing and activity so the results don't be good at all but they allow us to have an idea about how works our body. In this project I haven't calculated the radiation lost so the temperature actually will be lower

In general as is logical for the same activity if the value of the clothing is higher, the temperature is also higher due to each time you are putting more layers of clothes and in consequence you are more insulated.

Continuous the instability around the head and the lower values take part in the right side of the body

5.3 TEMPERATURE OF THE CLOTHING.COOLING CASE

This is the parameter which measures the temperature of the outside surface of the clothes that the manikin is wearing.

5.3.1 Clothing temperature according to the clothing

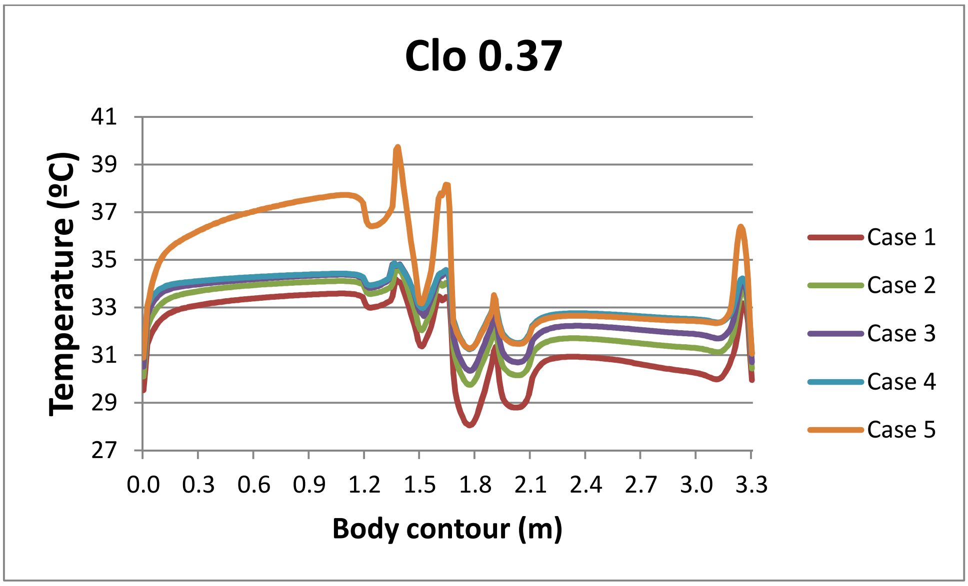

Fig 5.13. Clothing temperature in the cooling cases with 0.37 clo (ºC)

The cases with low activity have almost the same tendency even in the head zone where more turbulences we can find. The temperatures in these cases are between 33 and 35ºC in the left part and between 31 and 33ºC in the right side.

I want to point that in the case 5 (the which one with the most activity) in the right side it has normal temperature values but on the other side reaches values of 40ºC which are not typical

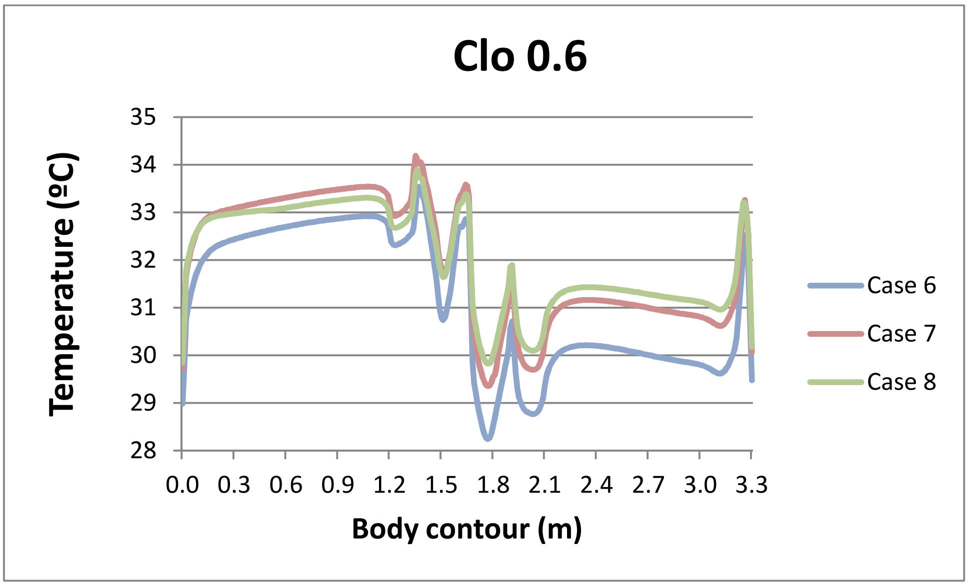

Fig 5. 14 Clothing temperature in the cooling cases with 0.60 clo (ºC)

In this graphic we can see a big rise and drop in the extremes of the contour. There isn't a great difference among all the cases even the case 7 has a trend in which reaches more temperature than the case 8 in spite of having less activity but the difference is very little.

In the right side it shows a bigger leap between the maximum and the minimum value than in the left part of the body because the heat flux is more affected by the air flow

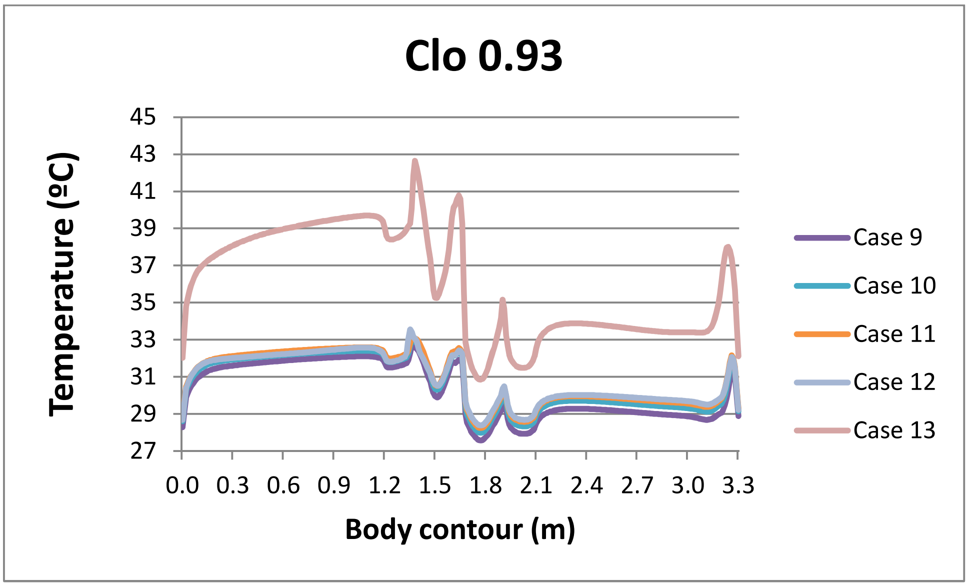

Fig 5. 15 Clothing temperature in the cooling cases with 0.93 clo (ºC)

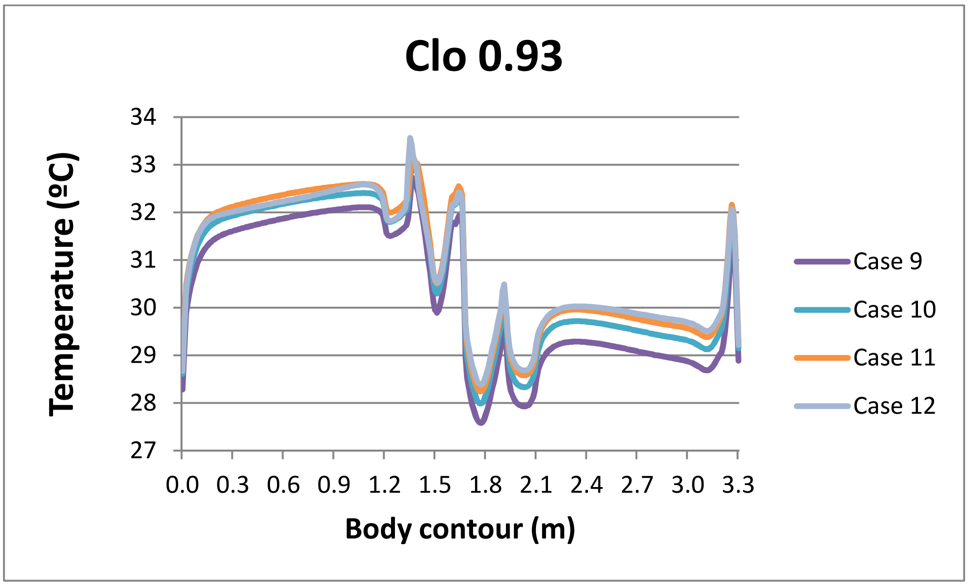

Fig 5.16 Detail of the clothing temperature in some cooling cases with 0.93 clo (ºC)

Here we can observe again the big leap between the cases with low/medium activity and the case with high activity.

The changes (rises and falls) in the case number 13 are more clear and it reaches temperatures up 43ºC.However the rest of the cases have values between 28 and 33ºC which practically are superposed each other mainly in the left side of the body.

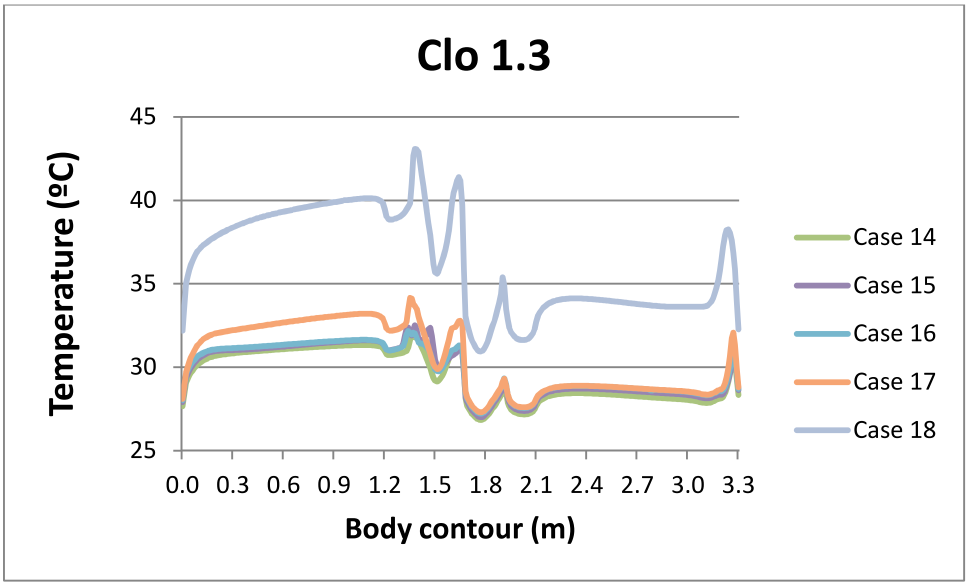

Fig 5. 17 Clothing temperature in the cooling cases with 1.3 clo (ºC)

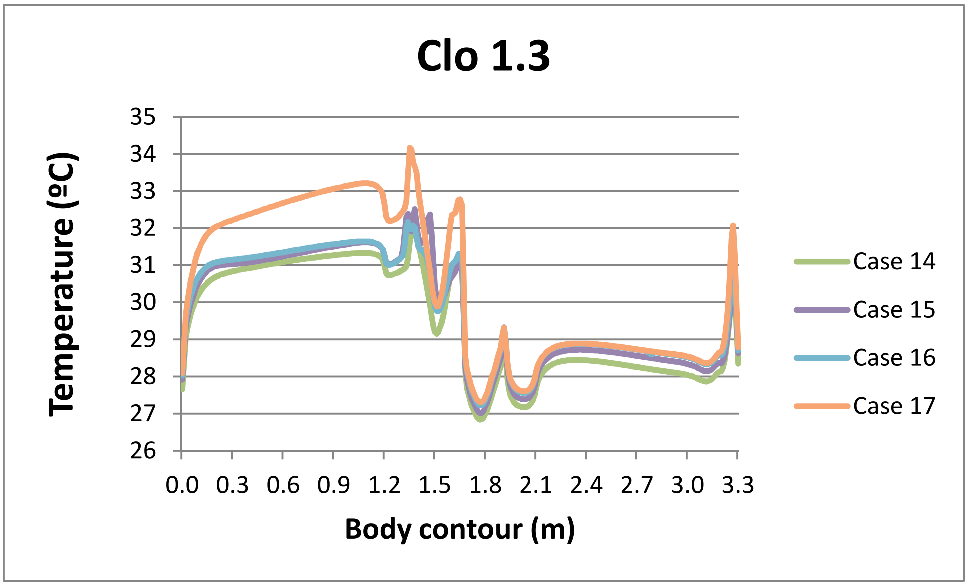

Fig 5. 18 Detail of the clothing temperature in some cooling cases with 1.3 clo (ºC)

The difference between this graphic and the previous one is that the case 17 shows some instability as consequence of being a case with high value of clothing and activity, mainly in the left side because in the other part the temperature is the same as the case 16 due to the refrigeration that the evaporation of the sweat produces in the human body

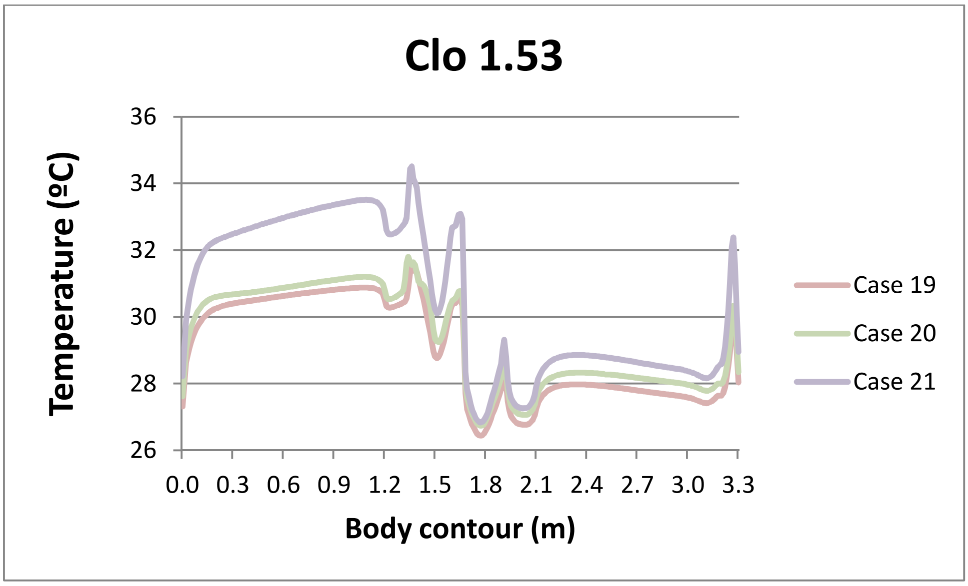

Fig 5. 19 Clothing temperature in the cooling cases with 1.53 clo (ºC)

Here the case with and activity of 3 met (case 21) has higher values the the other two cases but they are acceptable.

The tendency of the three cases is very similar.

In general the cases with low activity reach lower temperatures due to the heat that the body produces (metabolic heat) is lower as less worked up is the action.

The value of the temperature in the higher activity (6 met) cases is well above the rest of the cases so here we can see the influence which has the generation of metabolic heat.

On the other hand, in all the cases the left side of the body reaches higher temperature than in the right side. In the left (viewed from the front) the air flow is lesser than in the right because the heat supply is on top-left of the room and doesn’t affect too much to this part of the body as we can see in the velocity vectors graphics of the section 5 of this project.
The air creates a boundary layer above the clothes which makes to rise the temperature because it doesn’t change and is heating with the passage of time and also due to the low flow the lost by evaporation are very small
The heating lost by convection in this side will we higher than in the right because the difference of the temperature among the adjacent layer of the clothes and the surrounding air is bigger, however the movement of the air in the right side will cause more lost by evaporation.

Also is important to notice that in all cases in the final part of the contour there is a upturn of the temperature due to in this part of the body the air flow is almost zero and produces a similar effect as in the left side of the body
At the beginning of the contour also we can see this effect, the air is still so the temperature is very low but then start to rise little by little

5.3.2 Clothing temperature according to the activity

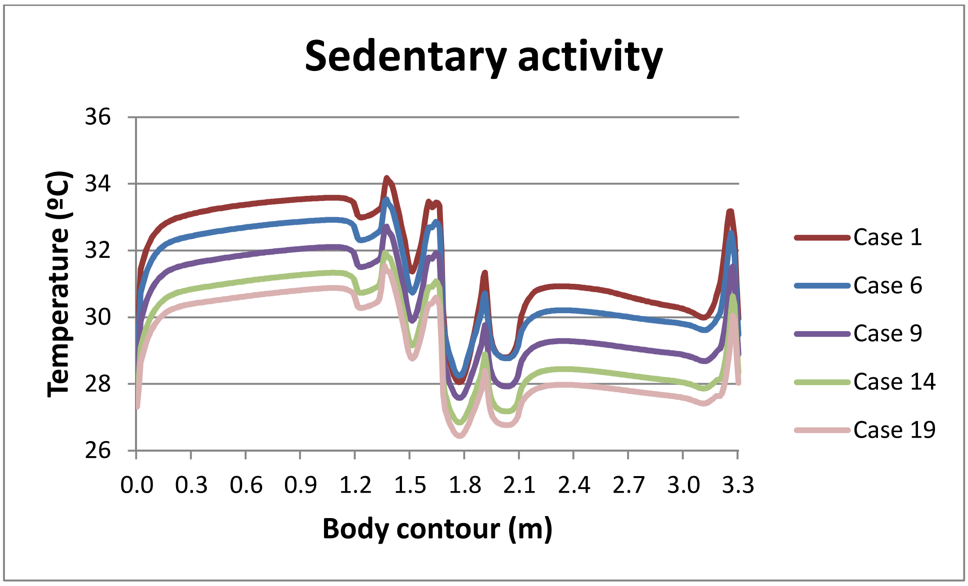

Fig 5.20 Clothing temperature in the cooling cases with sedentary activity (ºC)

This temperature graphics have the same tendency only separated by the value of clothing. If the clothing is low the temperature is higher because is easier to evacuate the heat and therefore the temperature rises due to the lesser isolation.

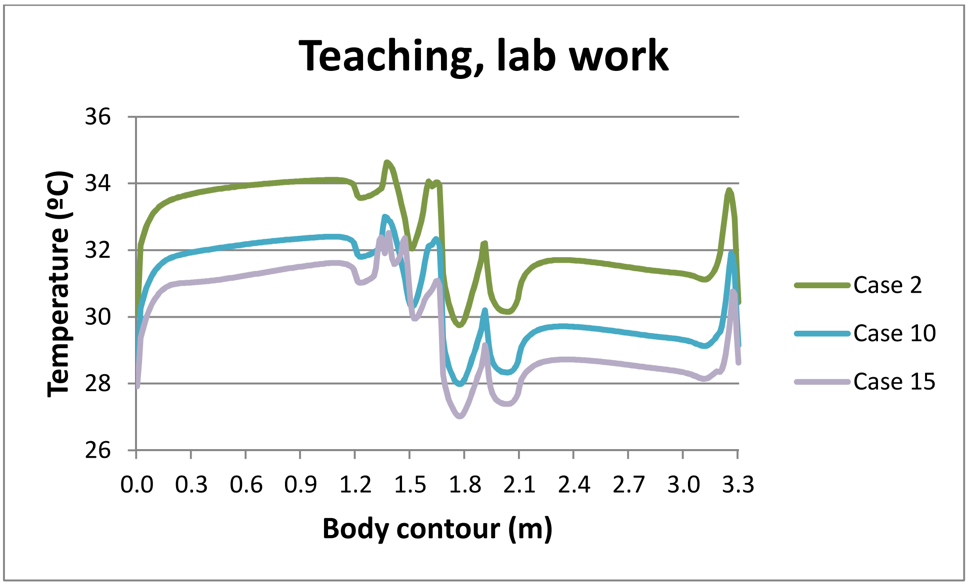

Fig 5.21 Clothing temperature in the cooling cases of teaching, lab work (ºC)

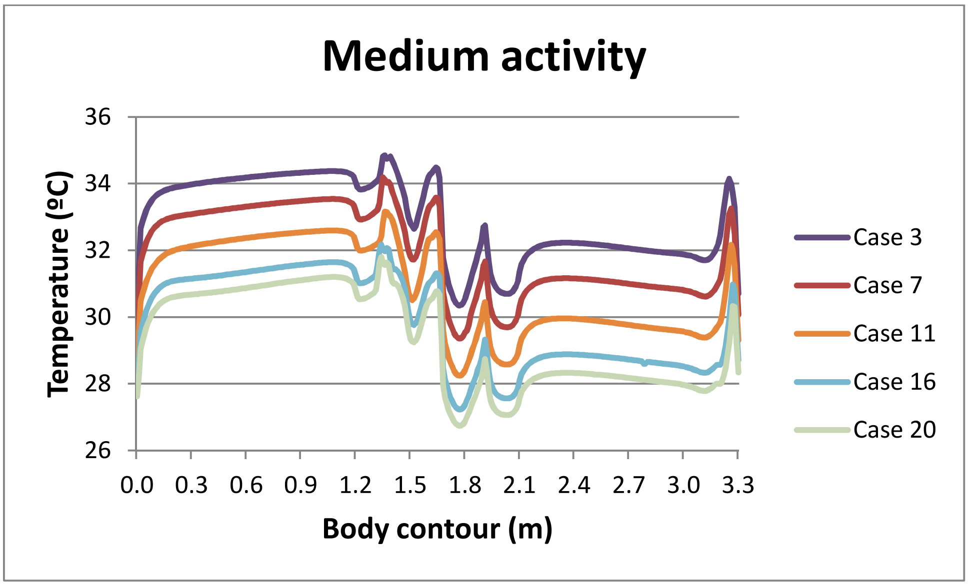

Fig 5.22 Clothing temperature in the cooling cases with medium activity (ºC)

In the two previous graphics we can see that the equality of the tendency is keeping in the different cases but if the activity is medium the temperature is a little bit on top of the case of being on lab.

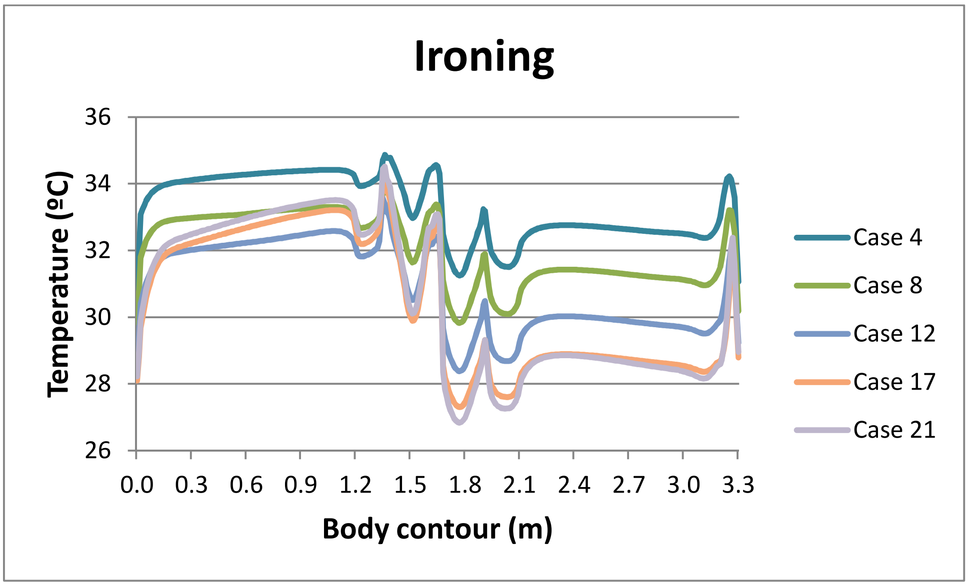

Fig 5.23 Clothing temperature in the cooling cases of ironing (ºC)

The most representative in this graphic is that the cases with higher clothing don't follow the tendency of the other three because in the first part of the contour the cases 17 and 21 are superposed with the cases 8 and 12but later in the head zone and in the last part they return to the normality.

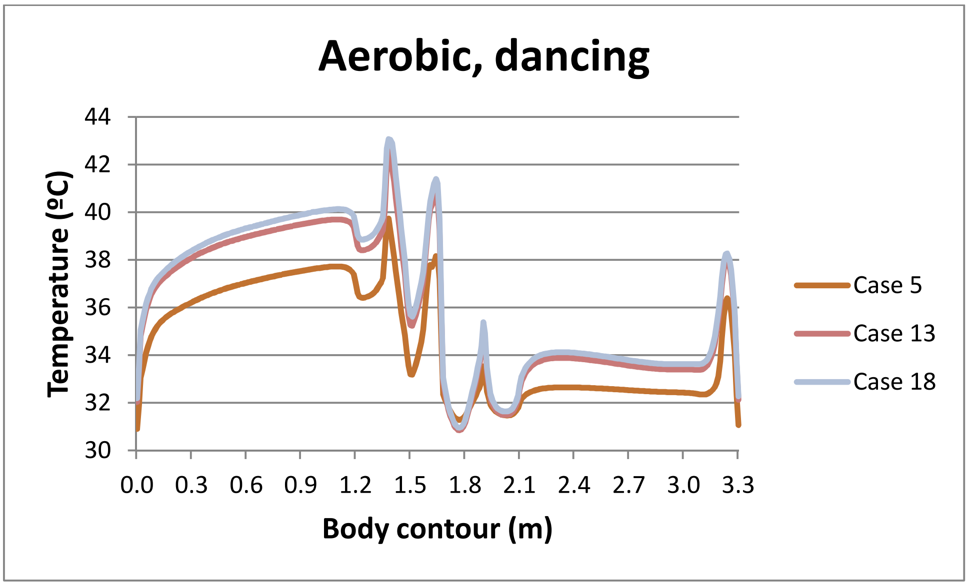

Fig 5.24 Clothing temperature in the cooling cases of aerobic, dancing (ºC)

In this high activity case the tendency changes because the case 18 is which has more clothing marks the higher temperature. We have reached a point where the heat generation is as high that the insulation which the clothes provide is insufficient and stop having effect and, in consequence the clothes reach high temperatures which are unnatural because we are analyzing cases with one kind of activity and high values of clothing except the case 5 where the temperatures are acceptable

In general the graphics show that for the same activity as higher clothing, the surface temperature of the clothes is lower because it has more insulation and the heat flux has more difficulties to go out of the body.

The thing which doesn't suffer any change is the instability in the part around the head because it doesn't have protection and is easier to lose heat. Also the temperature in the right side of the body is lower than in the left side

5.4 TEMPERATURE OF THE SKIN. NO COOLING CASE

This is the parameter which measures the temperature of the skin of the manikin which is in direct contact with the clothes.

5.4.1 Skin temperature according to the clothing

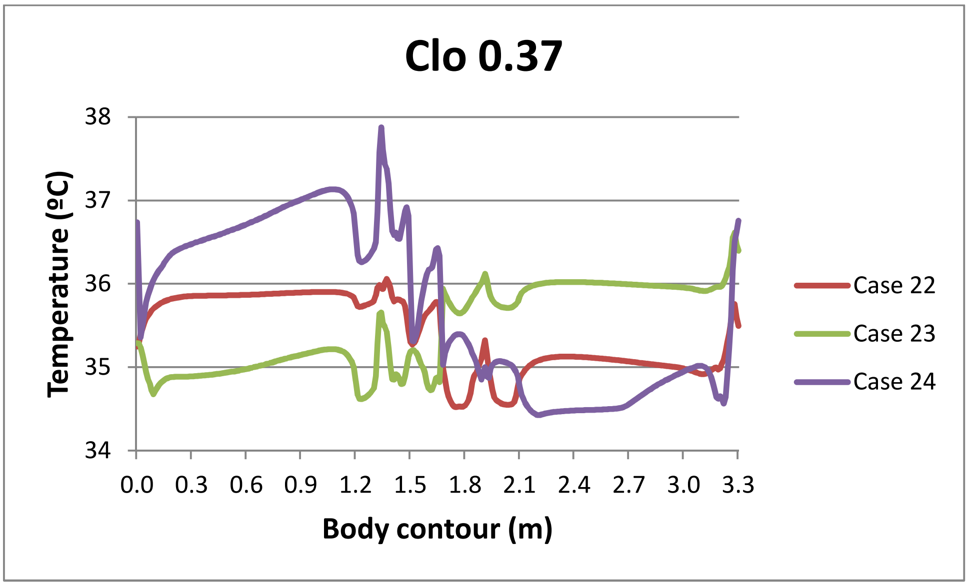

Fig 5.25 Skin temperature in the no cooling cases with 0.37 clo (ºC)

This graphic is practically the same as in the case of no cooling and 0.37 clo. The highest activity case in the initial part (left side of the body) has the greatest temperature but after the head is lower due to is not excessively insulated of the air flow because it's dressing not too much clothes, therefore the sweat of the skin evaporates easier and refrigerates more but in the first part this is not possible because we don't have almost no air flow

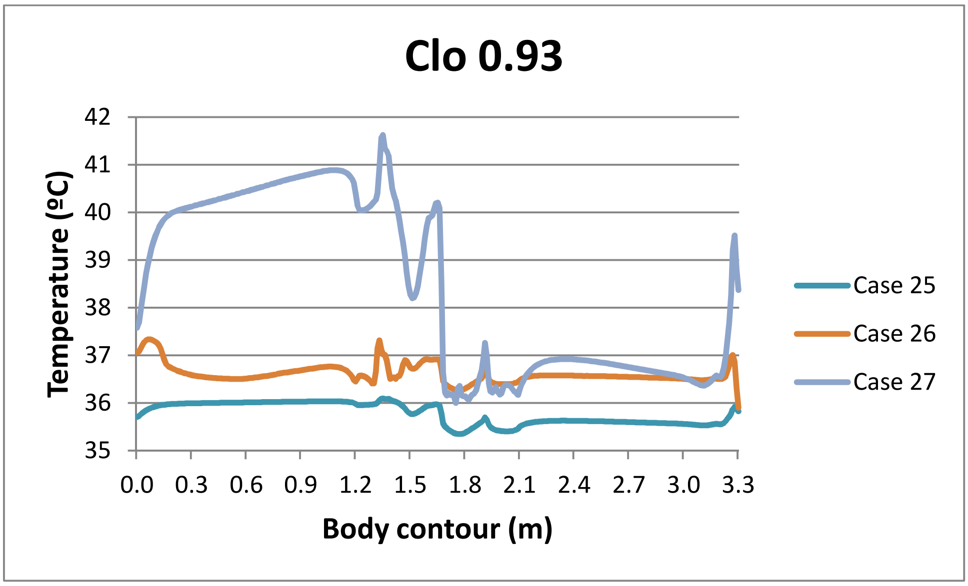

Fig 5. 26 Skin temperature in the no cooling cases with 0.93 clo (ºC)

However here the case with more clothing is in almost all the contour above the rest of the cases because is wearing more layers of clothes which limit the effect of the air in the skin, therefore the evaporation of the sweat is also limited.

We can see as lower is the activity lower is the skin temperature because the metabolic heat generated by the body is also lower.

The values in general are high but mainly in the case27 because it reaches more than 41ºC which is not compatible with the life. But this case in not realistic because being ironing with this amount of clothes is not feasible.

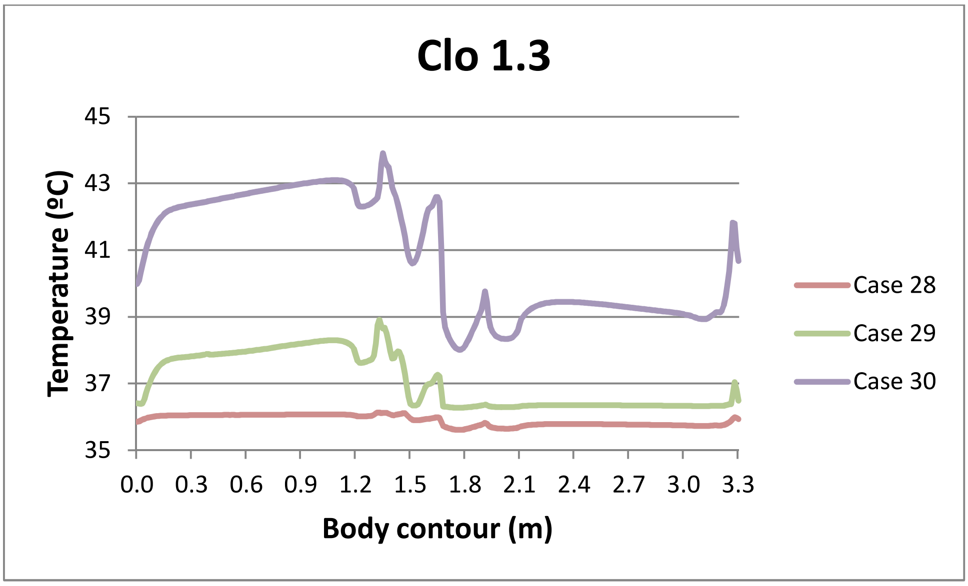

Fig 5. 27 Skin temperature in the no cooling cases with 1.3 clo (ºC)

Here the difference between the case with high activity and the cases with low/medium activity is clearer because the case 30 is above the other two and reaches 43ºC which has no sense. Even the temperatures in case 29 are high.
Another thing which attract attention is the case 28 because is almost linear even in the head area.
The high insulation that the body has causes that we reach this high temperatures because doesn't allow to evacuate the heat flux from inside to outside so as higher is the activity higher is the temperature as we can see.

5.4.2 Skin temperature according to the activity

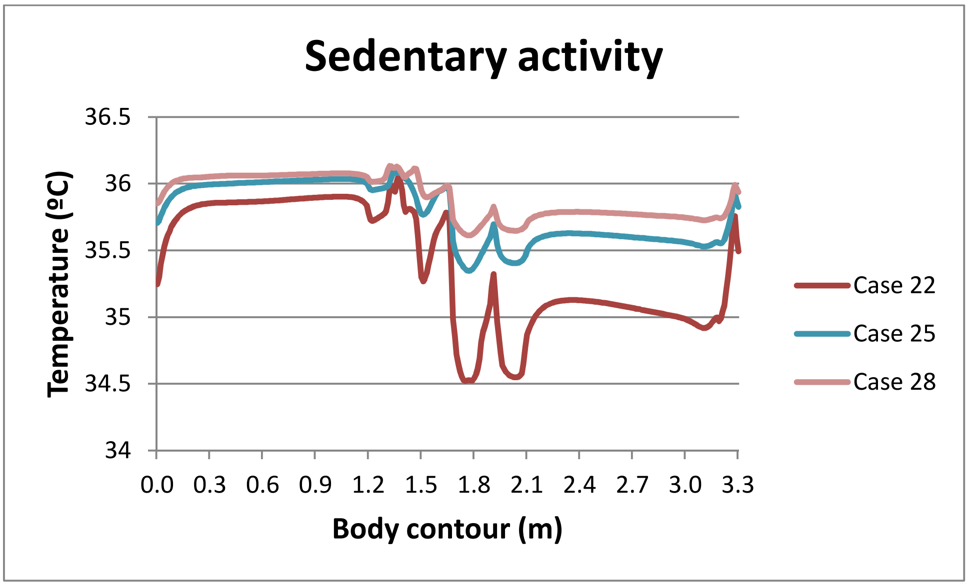

Fig 5.28 Skin temperature in the no cooling cases with sedentary activity (ºC)

In this graphic we can appreciate how for the same activity the clothing is a very important factor because as higher is the value of clo higher is the temperature due to the clothes don't allow the body to perspire. As fewer amount of clothes easier is to evacuate the heat and lower is the skin temperature.
The three cases have the same tendency, in the first part the differences are not too big but in the second yes as consequence of the air movement. In the head area are some rises and falls alike.

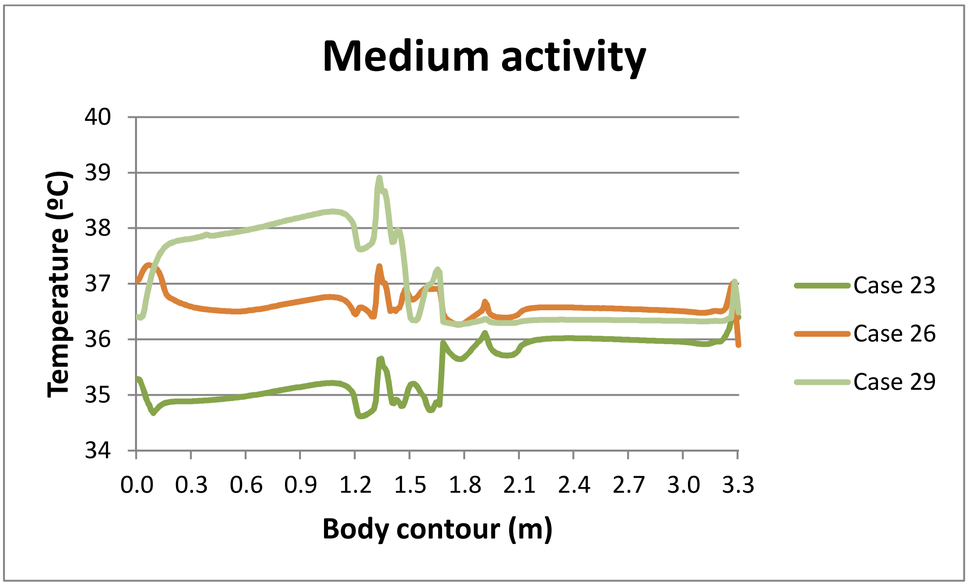

Fig 5.29 Skin temperature in the no cooling cases with medium activity (ºC)

The behavior of the body in this case is very similar to the previous one, the cases with high clothing have the higher temperatures except in the last part of the contour (right side) where the temperature of the case 29 is below the case 26, probably because it has more clothes and sweat more, in the right side the air flow evaporate more sweat so it refrigerates more but in the left side is not the same because we don't have air movement.

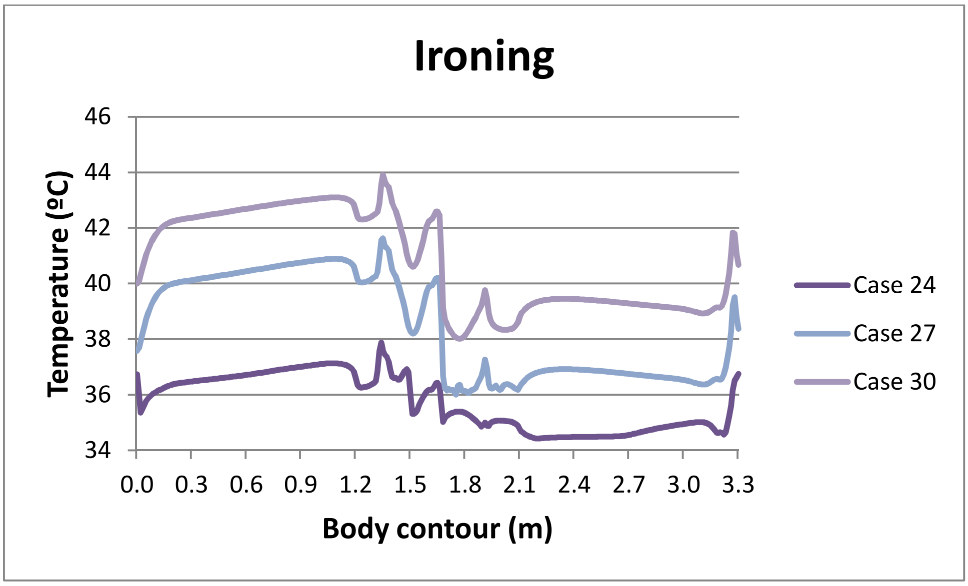

Fig 5.30 Skin temperature in the no cooling cases of ironing (ºC)

Here the situation is the same as in the previous graphic but with the differences more clear and highest temperatures which indicate that is impossible to iron or some similar activity during the summer with the clothing and the conditions that we are using to make the calculations

5.5 TEMPERATURE OF THE CLOTHING. NO COOLING CASE

This is the parameter which measures the temperature of the outside surface of the clothes that the manikin is wearing. Now the inlet air has a temperature of 28ºC.

5.5.1 Clothing temperature according to the clothing

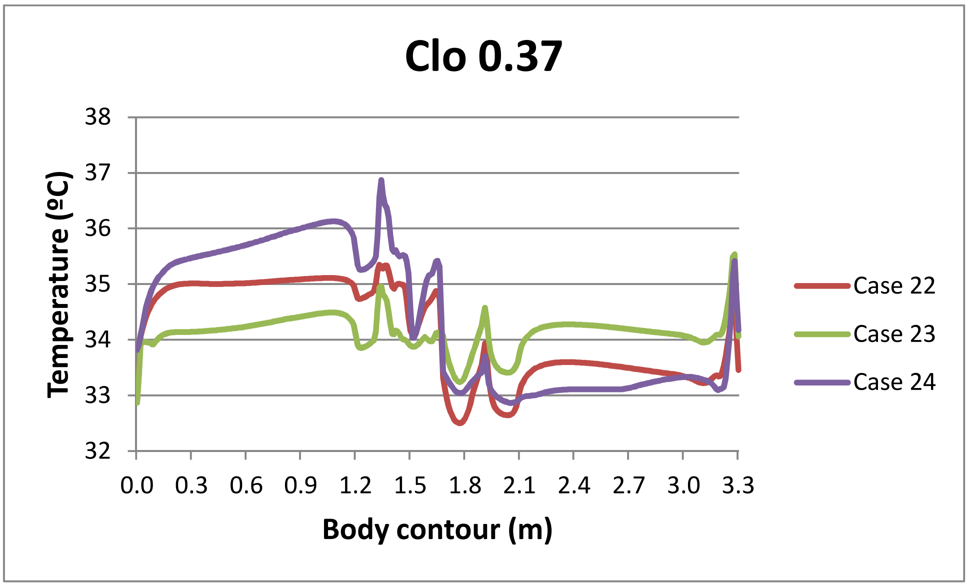

Fig 5.31 Clothing temperature in the no cooling cases with 0.37 clo (ºC)

Here the values of the case 24 (the highest activity) are different because the first part of the contour has the highest temperatures but then in the head area and in the last part don't happen the same.

The case 22 should have the lowest temperatures along the contour but is not so. It marks punctually the minimum temperature but in the rest of the graphic the values are among the values of the cases 23 and 24

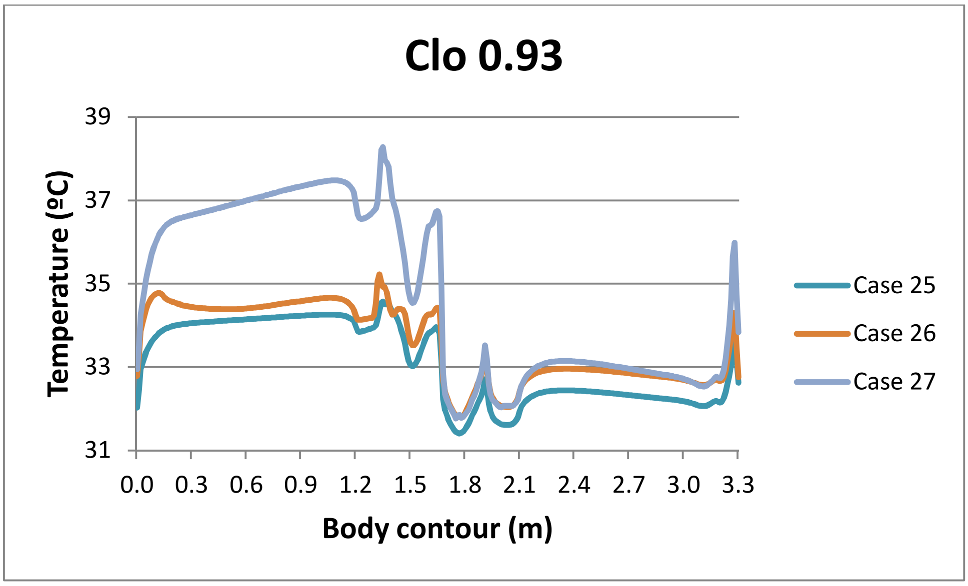

Fig 5. 32 Clothing temperature in the no cooling cases with 0.93 clo (ºC)

In this graphic we can see that the case with more activity has the highest temperature, although at the end is almost the same as the case 26.

All the graphics follow the same tendency more or less but it's true that in the case 27 the temperature reaches punctually values that aren't realistic of around 38ºC.

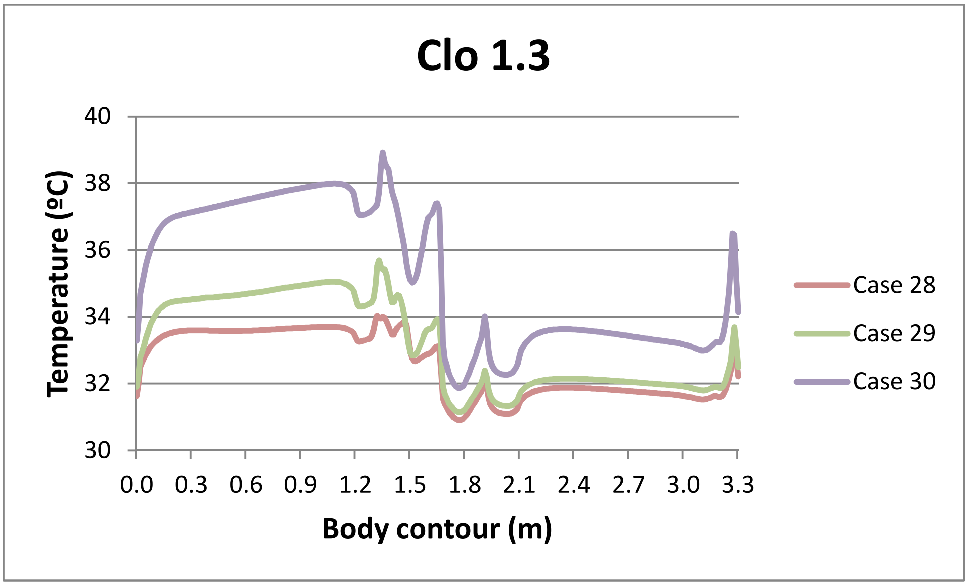

Fig 5. 33 Clothing temperature in the no cooling cases with 1.3 clo (ºC)

The temperatures reach by the case 30 are excessively high along he left side of the body, no punctually.

We have to realize that the air temperature of the inlet input is 28ºC and the activity of the cases is medium/high (3met) and I have obtained high values so we can understand what happened when we don't have air conditioning and we make some effort (is not necessary to be a big effort).

The values of the cases with low activity are normal, between 31 and 35 ºC and all the cases have the same tendency more or less

5.5.2 Clothing temperature according to the activity

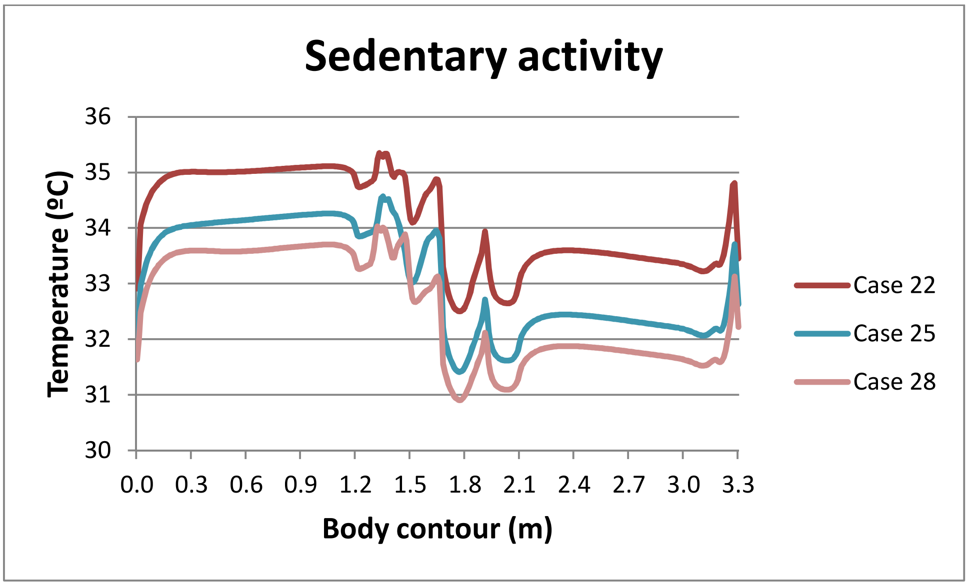

Fig 5.34 Clothing temperature in the no cooling cases with sedentary activity (ºC)

In this graphic the values of the clothing temperature are completely normal because as we can see the case with more insulation (clothing) has the lower temperature and the case 22 is the which one with lees clothing and has the higher temperature on the surface of the clothing. The values are between 31 and 35 ºC.

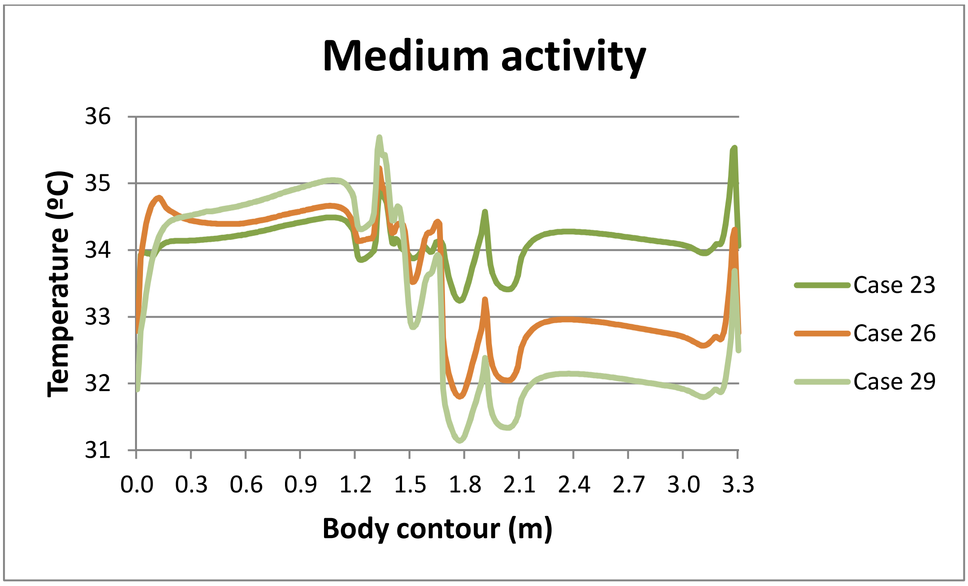

Fig 5.35 Clothing temperature in the no cooling cases with medium activity (ºC)

The most representative in this graphic is that the case with more clothing has the highest temperature in the left side of the body so the absence of air produces a higher heat flux by convection and not by evaporation. As there don't have evaporation there isn't cooling but the difference with the other cases is that here we have 28ºC of environmental temperature and medium activity so you sweat more, the consequence of this is that sweat is warming up with the heat that the body produces so the temperature rises.

After, the temperature of the case 29 is lower due to the movement of the air which favor the cooling of the body by evaporation because you sweat more.

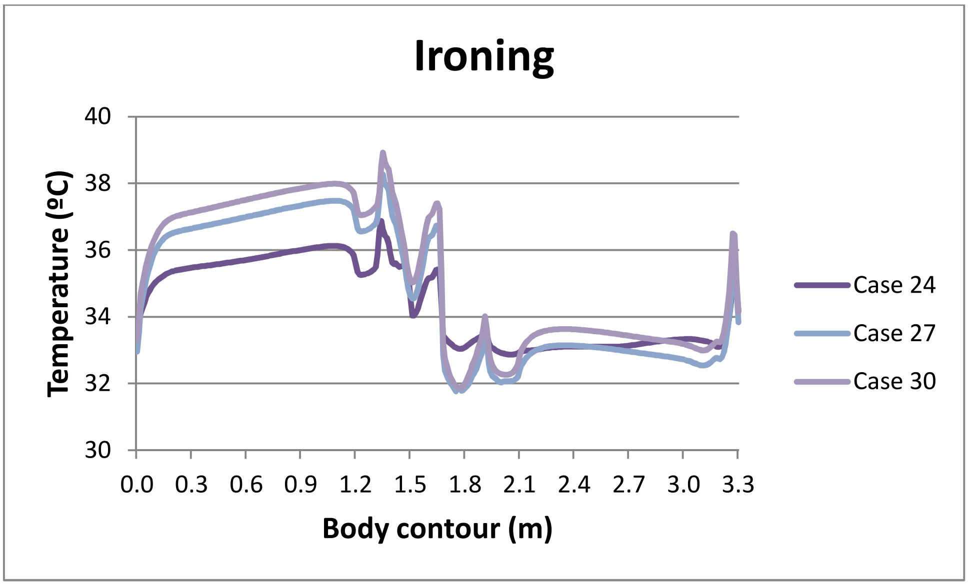

Fig 5.36 Clothing temperature in the no cooling cases of ironing (ºC)

Here the situation is the same as in the previous activity but with higher temperatures and along all the contour. The case number 30 has the maximum temperature in each sides of the body. Therefore we can deduce that ironing dressing a big amount of clothes insulates a lot and we can't evacuate the heat generated by the body so the temperature rises.

This is not a real case because nobody iron during the summer with trousers, long-sleeve shirt, long-sleeve sweater, t-shirt, suit jacket and long underwear bottoms.

5.6 DRY HEAT FLUX. COOLING CASE

In this section I'm going to analyze the quantity of heat that the human body gives to the surroundings because of his activity and the clothing.

5.6.1 Dry Heat flux according to the clothing

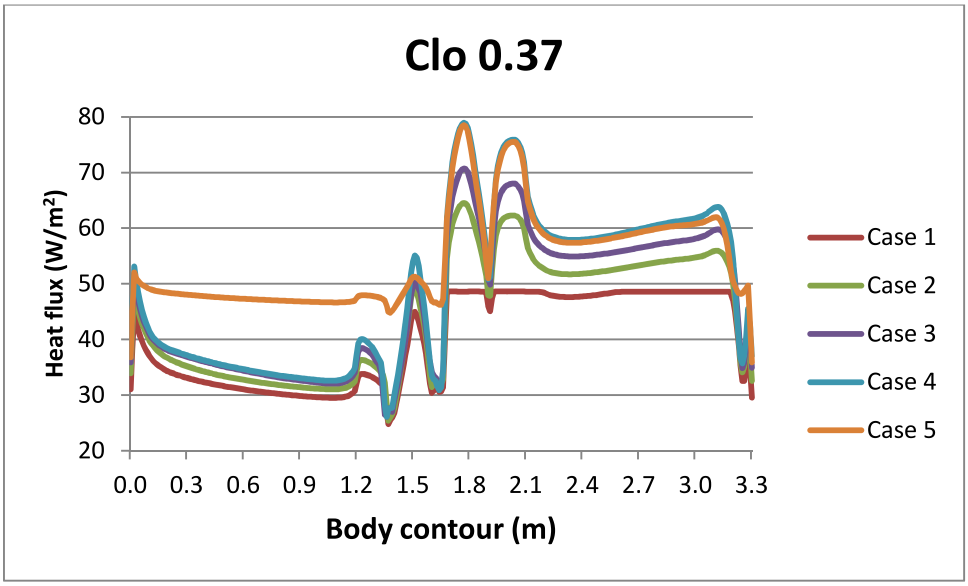

Fig 5.37 Heat flux in the cooling cases with 0.37 clo (W/m^2)

Here we have obtained values between 20 and 80 W/m^2. All the cases have almost the same tendency except the case 1 and the case 5 which in the last and first part respectively have a linear trajectory.

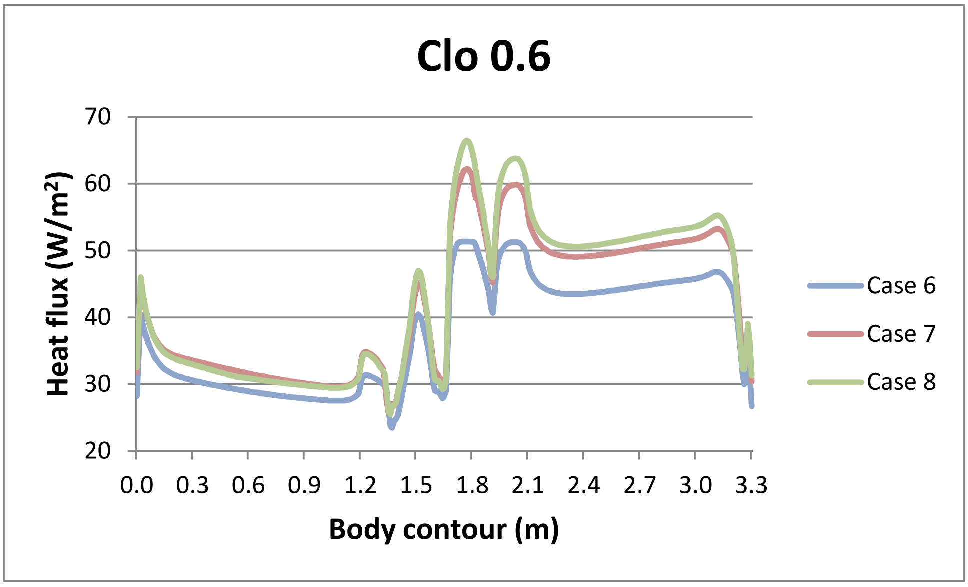

Fig 5.38 Heat flux in the cooling cases with 0.60 clo (W/m^2)

In this occasion the tendency is again the same for the three cases and the values aren't too much distant each other which indicate that for this clothing the influence of the activity is not very important.

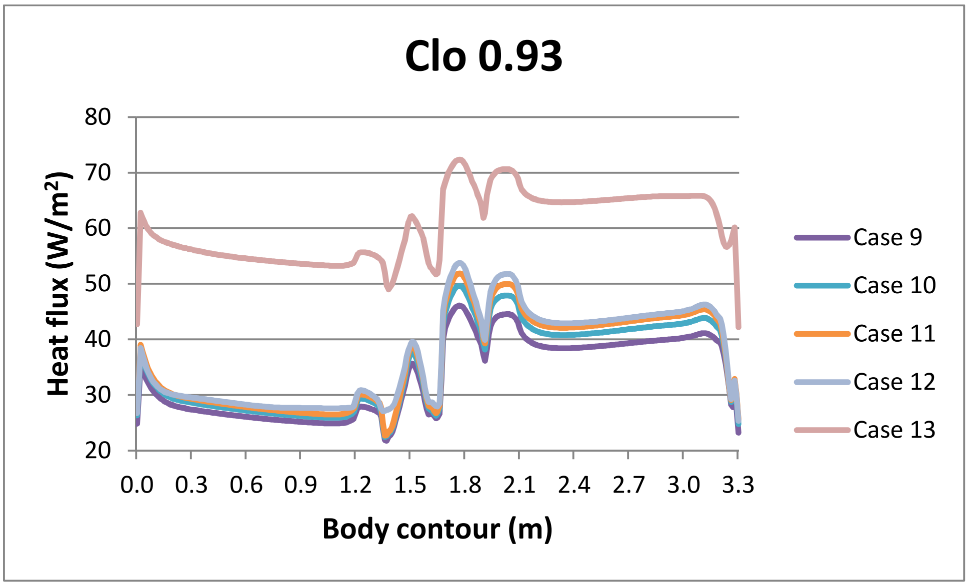

Fig 5.39 Heat flux in the cooling cases with 0.93 clo (W/m^2)

In this graphic we can see clearly how the cases with low/medium activity have values between 20 and 50 W/m^2 and however for the case number 13 with an activity of 6 met the minimum is 50 W/m^2 and the maximum is 75 w/m2 although the shape of all the graphics are the same.

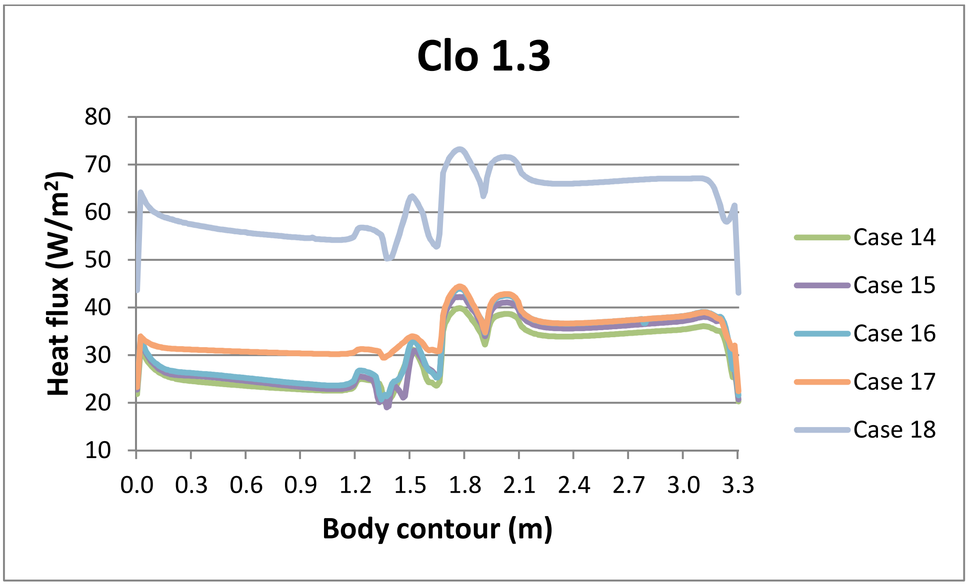

Fig 5.40 Heat flux in the cooling cases with 1.3 clo (W/m^2)

Here we see once again the leap from the other cases occurred when you make a heat flow analysis for an activity of 6 met.

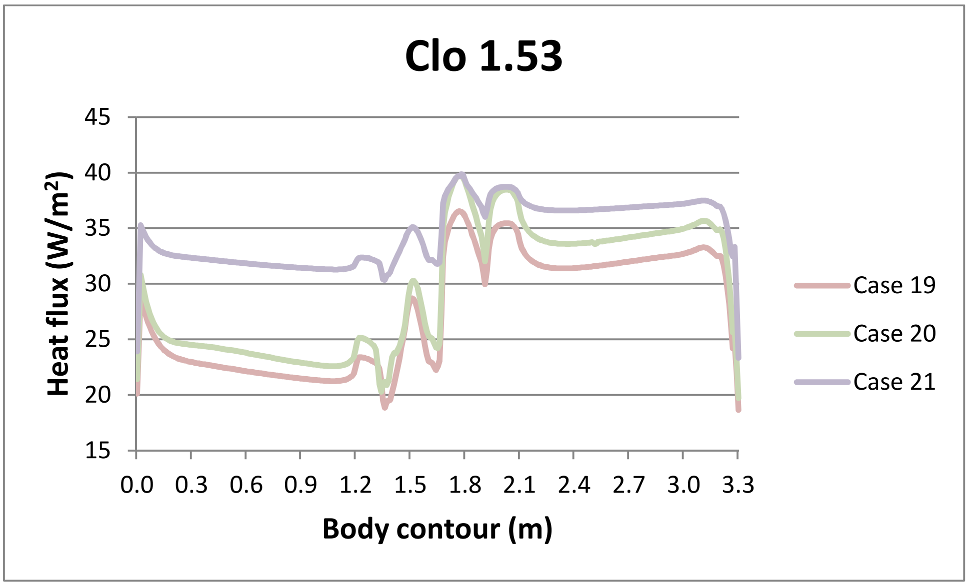

Fig 5.41 Heat flux in the cooling cases with 1.53 clo (W/m^2)

The difference among the cases is not too big but the range of the values is smaller, it is between 20 and 40 W/m^2.

In general for the same clothing as higher is the activity higher is the heat flux because the heat generated inside the body is higher and the isolation due to the clothes is constant.

The value of the heat flux for the cases with low/medium activity is in almost all the graphics very similar each other but when the activity is high that case marks the maximum value.
Moreover all the graphics have a little step at the beginning, a light but continuous rise until the head area, here is where we find instabilities with a lot of leaps and then one part with a continuous rise til a downward step at the end of the contour (right foot)

Also is common to all the graphics that the last part of the contour (right side of the body) is where higher is the heat flux evacuated due to here the air flow is bigger than in the left side of the model and therefore this favor the heating lost by evaporation of the sweat generated with the activity.

Furthermore I want to emphasize that as bigger is the value of the clothing, the values of the heat flux are lower each time due to the higher isolation caused by the clothing

5.6.2 Dry Heat flux according to the activity

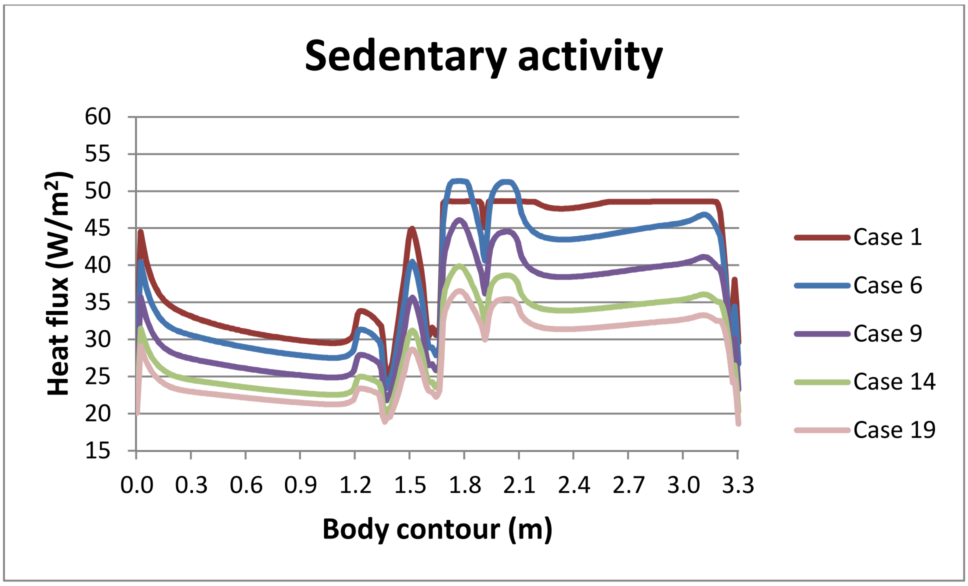

Fig 5.42 Heat flux in the cooling cases with sedentary activity (W/m^2)

This graphics have almost the same shape and the values aren't too much different each other. We have values between 20 and 25 W/m^2

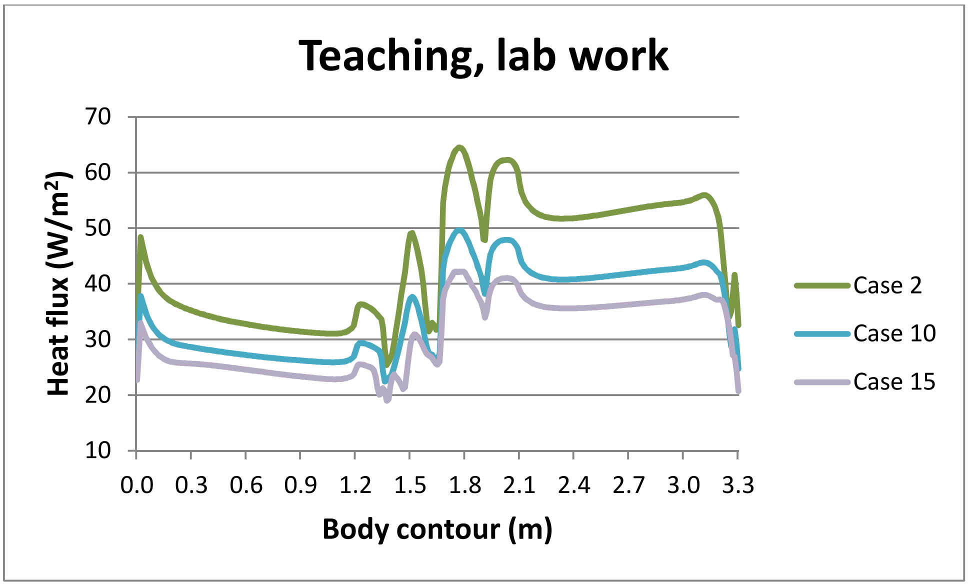

Fig 5.43 Heat flux in the cooling cases of teaching, lab work (W/m^2)

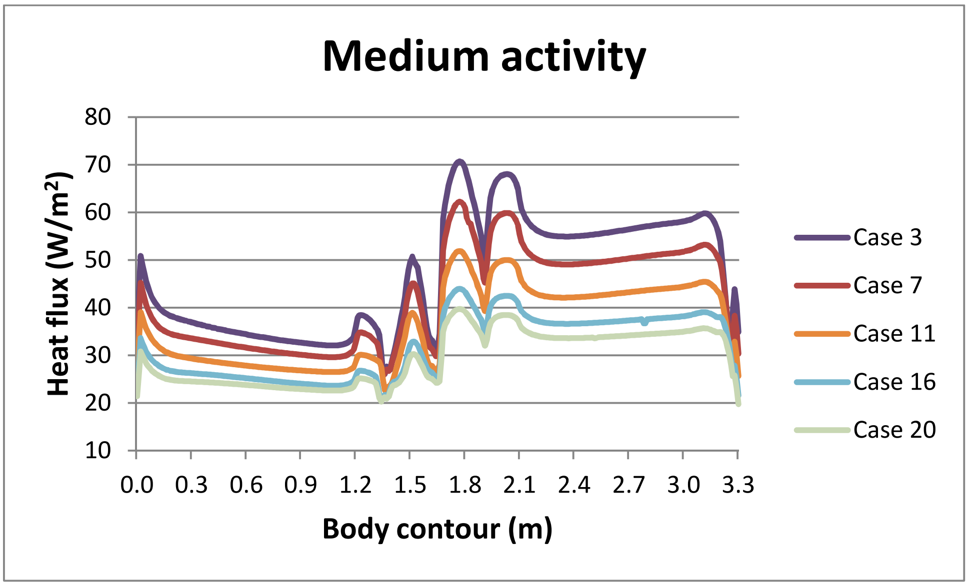

Fig 5.44 Heat flux in the cooling cases with medium activity (W/m^2)

The two previous graphics have values between 20 and 70 W/m2 and the lines follow the same tendency although the distance in the second graphic between each case is a little bit higher.

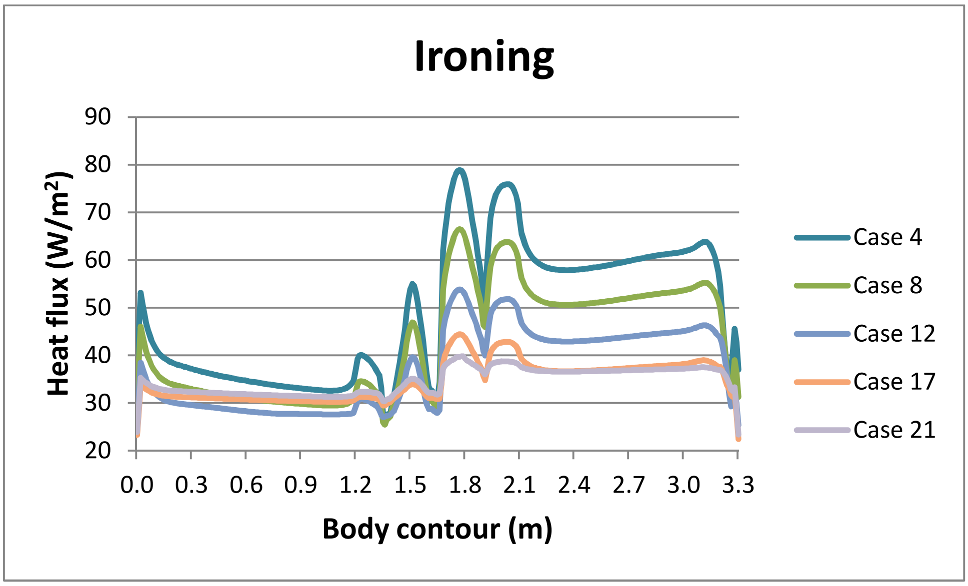

Fig 5.45 Heat flux in the cooling cases of ironing (W/m^2)

The most important here is that the cases 17 and 21 in the final part have the shape as we have seen until now, however the first part of the contour (left side of the body) is showing what are going to happen when the activity is dancing, aerobic.

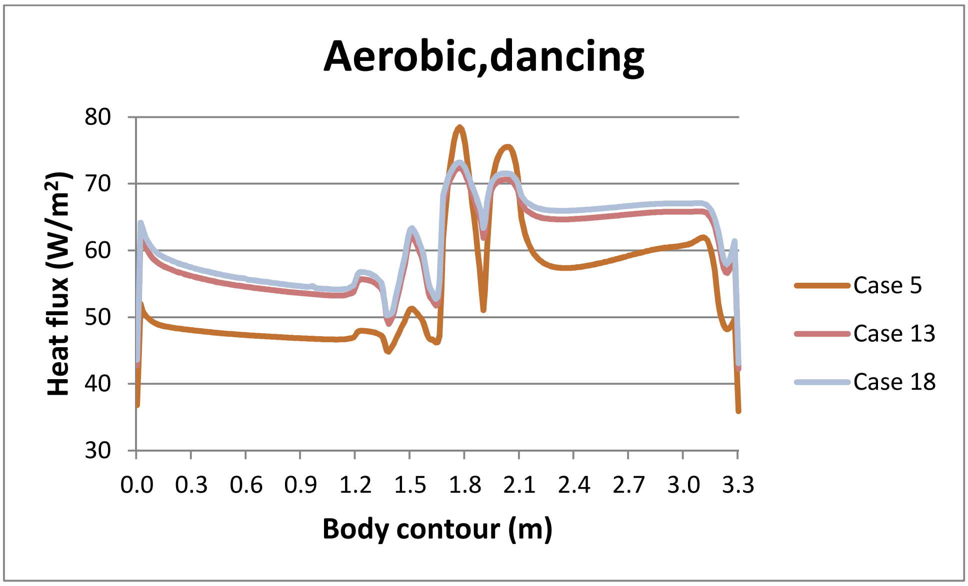

Fig 5.46 Heat flux in the cooling cases of aerobic, dancing (W/m^2)

With this activity we reach the higher heat flux values.

The most important is that now we have the opposite situation than before because here the case with higher clothing has heat flux values which are above the other two cases (although the maximum is marked punctually by the case 5) because the heat generated with the activity is so high that the insulation that the clothes can give doesn't affect and the heat evacuated is higher due to we sweat more and the evaporation is also higher..Also is true that in these cases the skin temperature is not realistic because the values are mortal.

In general in almost all the graphics we can see how for the same activity as lower is the clothing value the heat flux is rising because the isolation supplied by the clothes is lower and these make easier the heat transfer from the body to the environment. However there is an exception, when the activity is the highest one, dancing (6 met) it is not true as I have explained in the previous paragraph.

The value of the flux rises as higher is the activity because the generated heat is bigger so in the first graphic we are between 20-50 W/m^2 and in the last the values are between 30-80 W/m^2.

As with the temperatures we have instability in the central part of the contour (head area)

5.7 DRY HEAT FLUX. NO COOLING CASE

5.7.1 Dry Heat flux according to the clothing

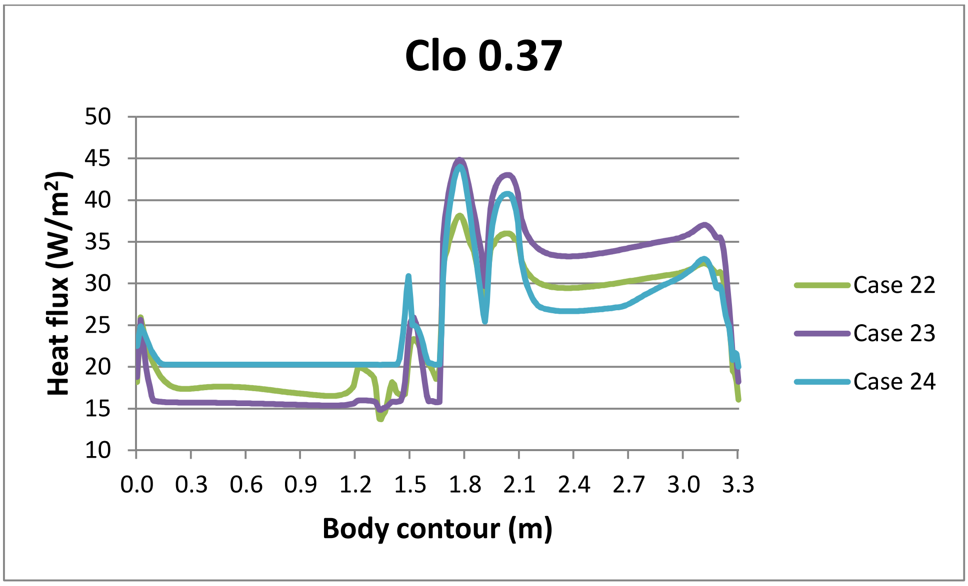

Fig 5.47 Heat flux in the no cooling cases with 0.37 clo (W/m^2)

This graphic has values between 15-45 W/m^2 and what I find remarkable is the strange behavior (in these values of clothing) of the case 24 because at the beginning marks the maximum value of the flux with a linear tendency but after it drops until the last position.

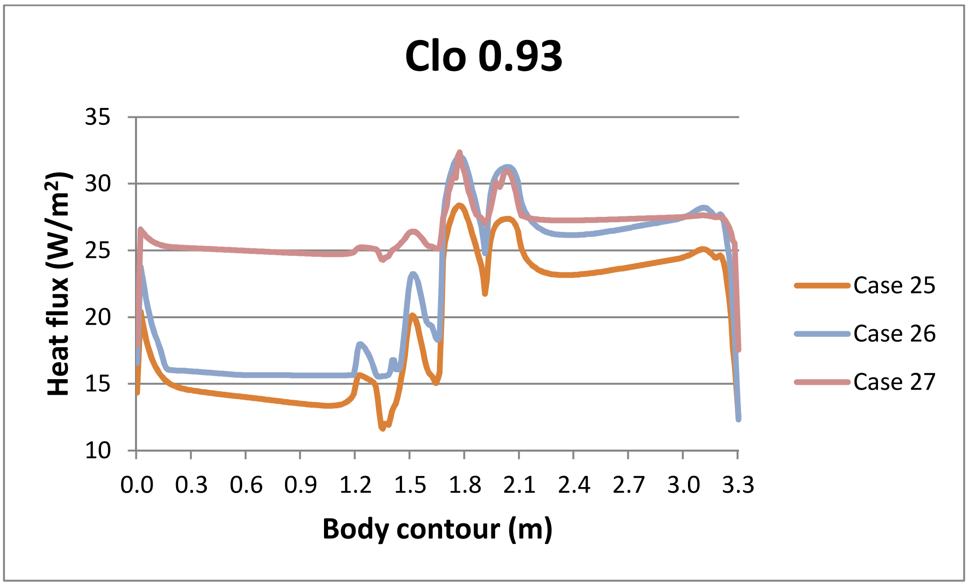

Fig 5. 48 Heat flux in the no cooling cases with 0.93 clo (W/m^2)

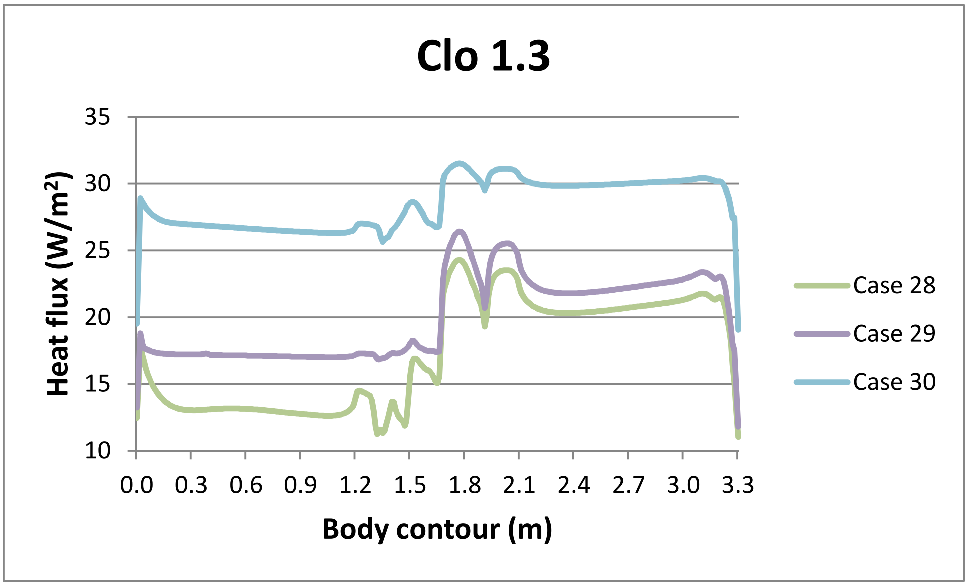

Fig 5. 49 Heat flux in the no cooling cases with 1.3 clo (W/m^2)

The two previous graphics show that the case with more activity is on top of the rest case but in the first graphic (0.93 clo) the case 26 is partially almost the same.
The case with less activity marks the minimum values due to the lower insulation because it has few layers of clothing.

The general comments that I have made in the previous section (5.6.1) are extrapolated to this section.

5.7.2 Dry Heat flux according to the activity

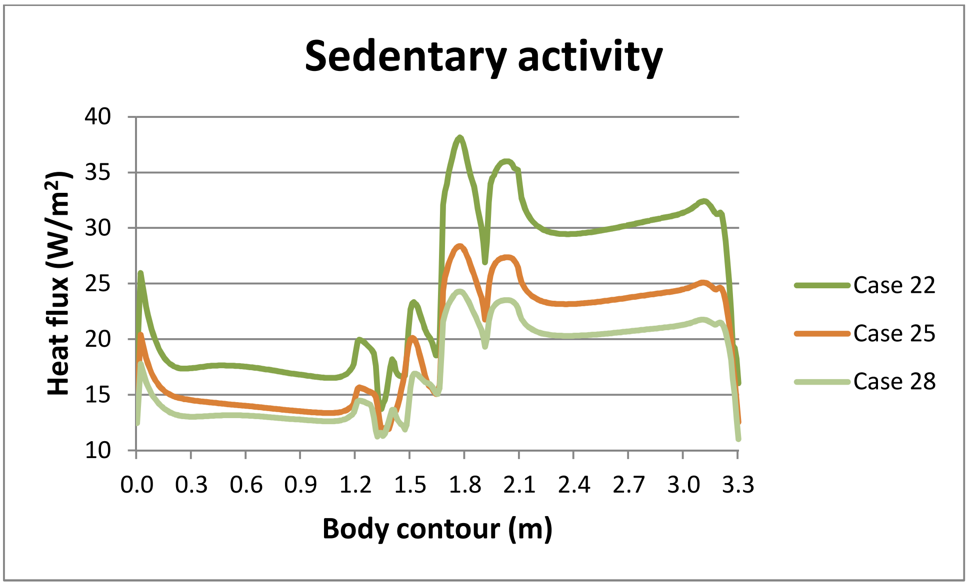

Fig 5.50 Heat flux in the no cooling cases with sedentary activity (W/m^2)

In this graphic we can see that they have quite irregularities but all of them have the same shape in the entire contour. The values are between 10-40 W/m^2

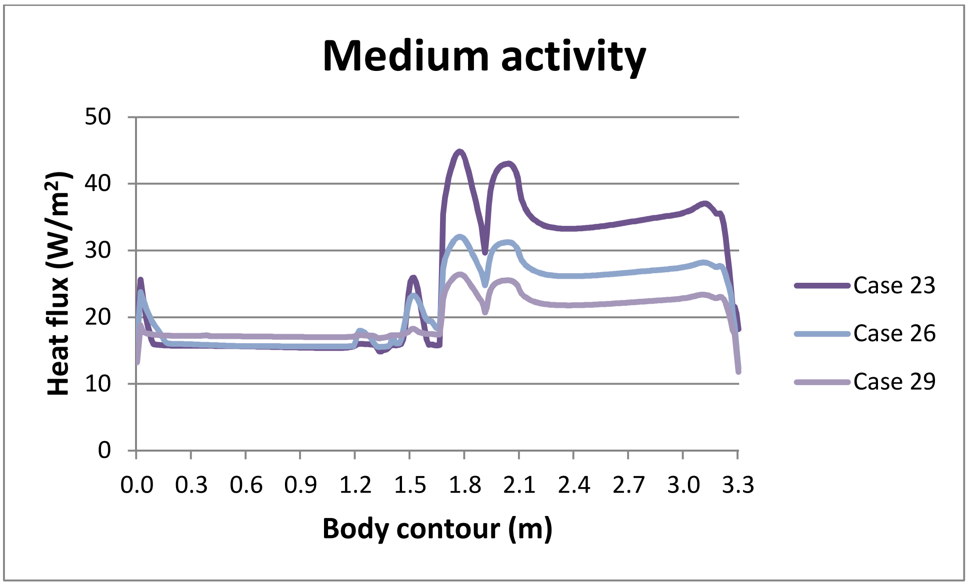

Fig 5.51 Heat flux in the no cooling cases with medium activity (W/m^2)

Here the most important thing is the linearity of the three cases in the left part of the model. Also they have the same tendency.

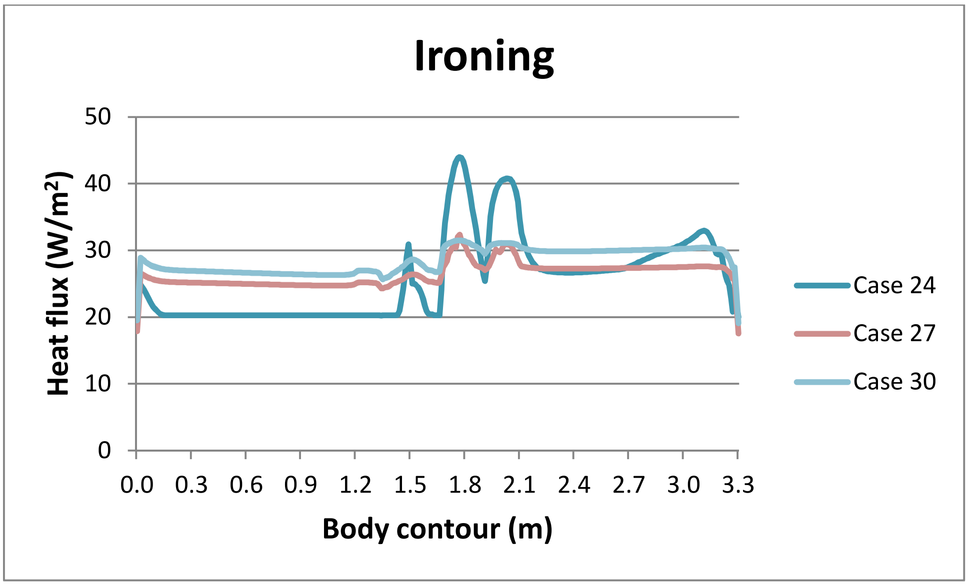

Fig 5.52 Heat flux in the no cooling cases of ironing (W/m^2)

The case 24 again shows an strange behavior, the other two cases follow the same shape. With this activity reaches the higher values of heat flux as is logical.
Here happen the same that when the was aerobic, dancing in the cases of cooling (as higher clothing, more evacuated heat) but with an activity with a lower met value because the environmental temperature is higher, so doing this activity the amount of

clothes scarcely influence due to the big quantity of heat generated and also because you sweat more, in consequence it evaporates more and evacuates more heat, but the true is that as more clothes more sweat.

The general comments of the section 5.6.2 can be extrapolated to here but I want to say that the values of the flux in the no cooling situation are lower in general due to the higher environmental temperature, and for example in the convection exchange the heat quantity is proportional to the temperature difference and in this case the difference among the temperature of the surroundings and the clothes is lower.

5.8 TEMPERATURE OF THE CLOTHING. COOLING VS NO COOLING

In this section I'm going to analyze the clothing temperature in the cooling and no cooling cases with the same value of activity and clothing in order to show what are the differences.

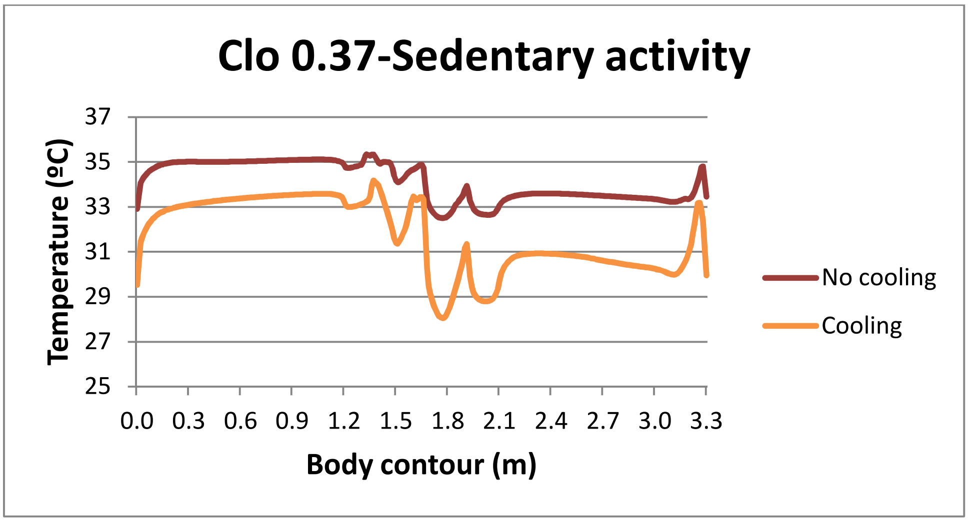

Fig 5.53Clothing temperature in cases with 0.37 clo and sedentary activity (ºC)

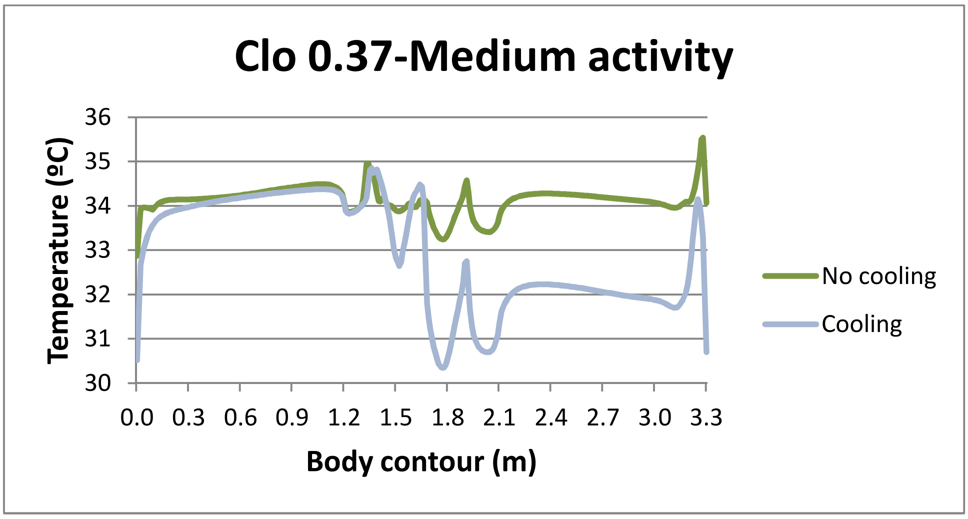

Fig 5.54 Clothing temperature in cases with 0.37 clo and medium activity (ºC)

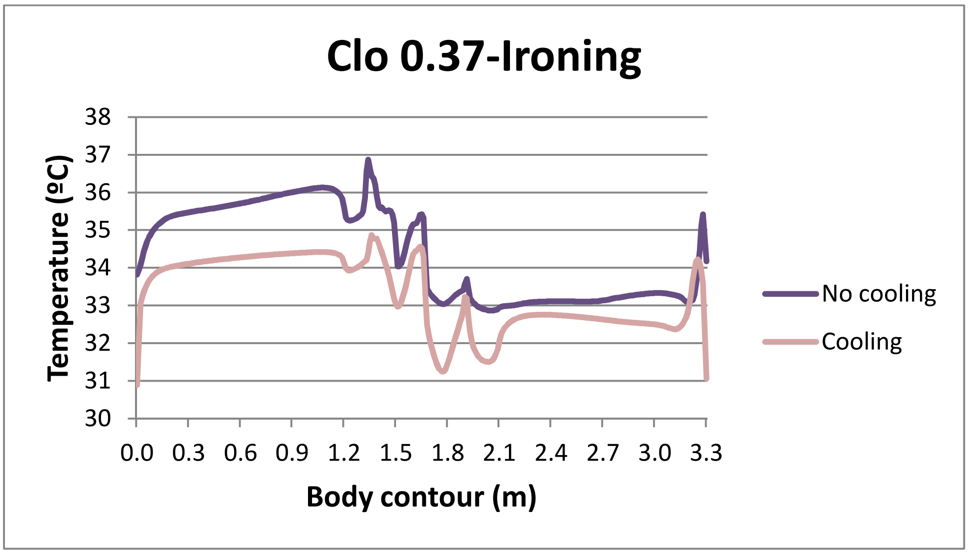

Fig 5.55 Clothing temperature in cases with 0.37 clo and ironing (ºC)

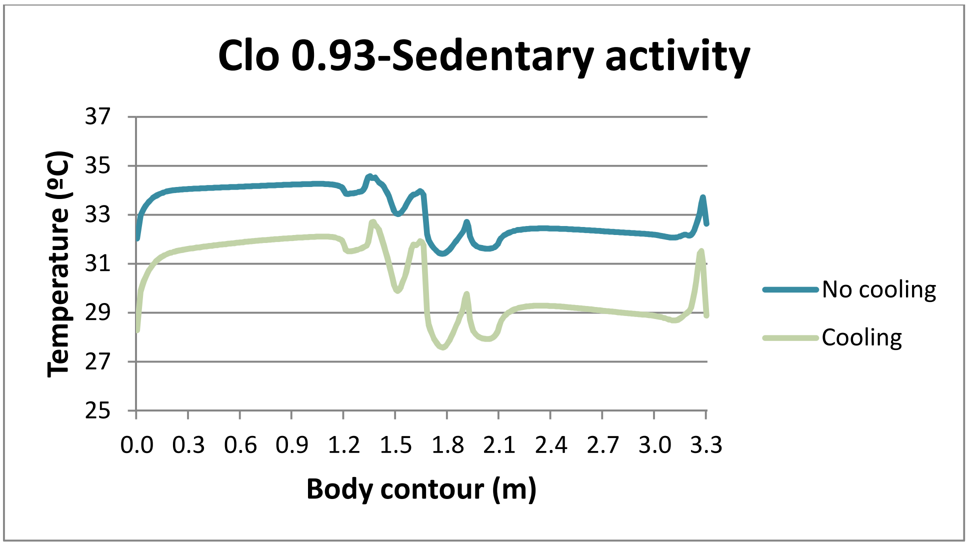

Fig 5.56 Clothing temperature in cases with 0.93 clo and sedentary activity (ºC)

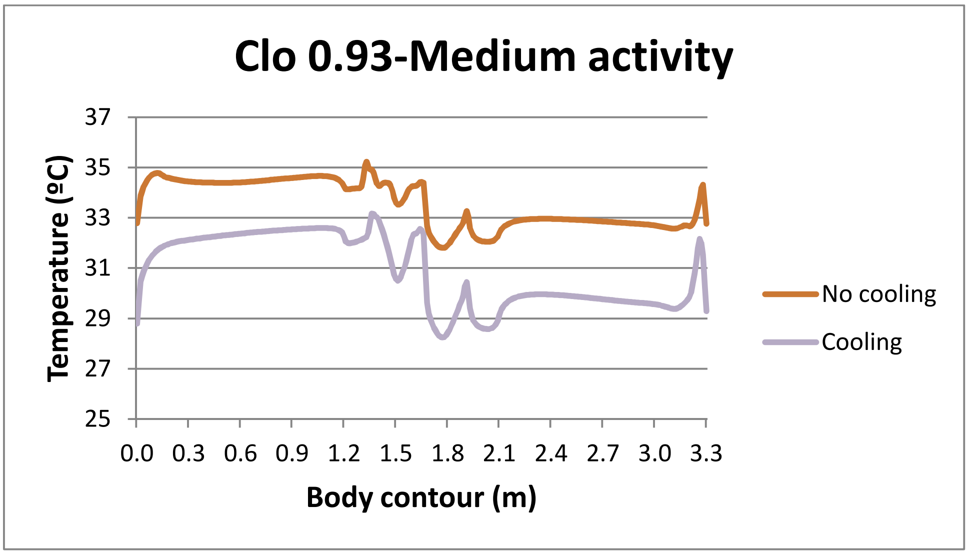

Fig 5.57 Clothing temperature in cases with 0.93 clo and medium activity (ºC)

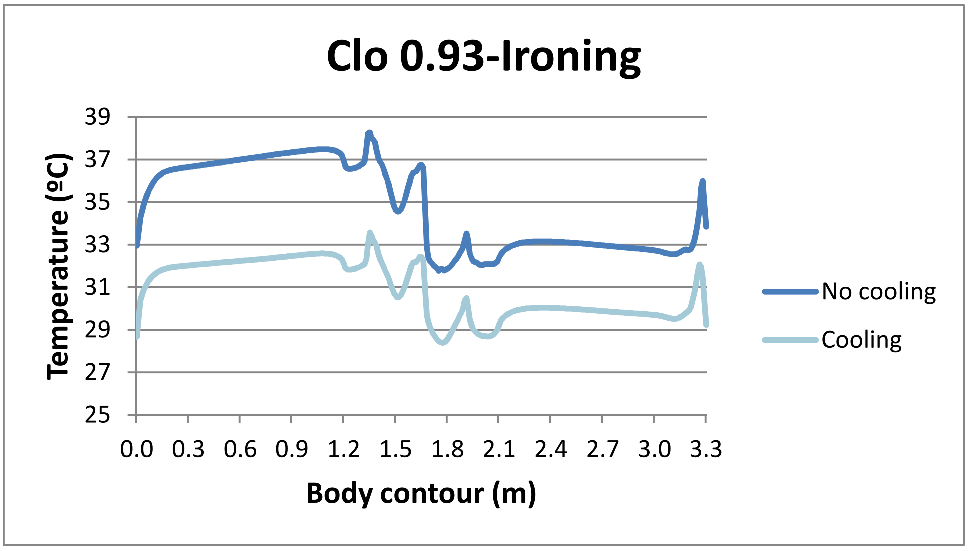

Fig 5.58 Clothing temperature in cases with 0.93 clo and ironing (ºC)

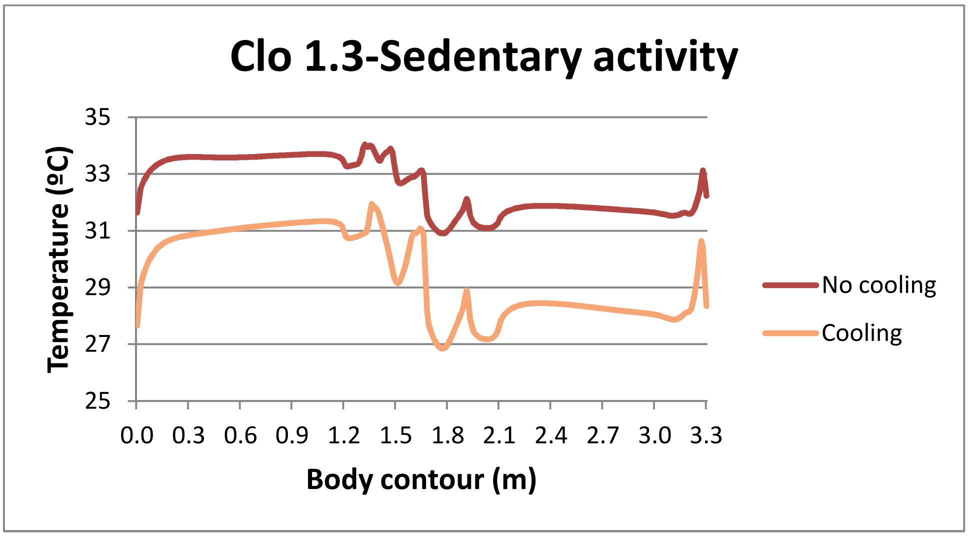

Fig 5.59 Clothing temperature in cases with 1.3 clo and sedentary activity (ºC)

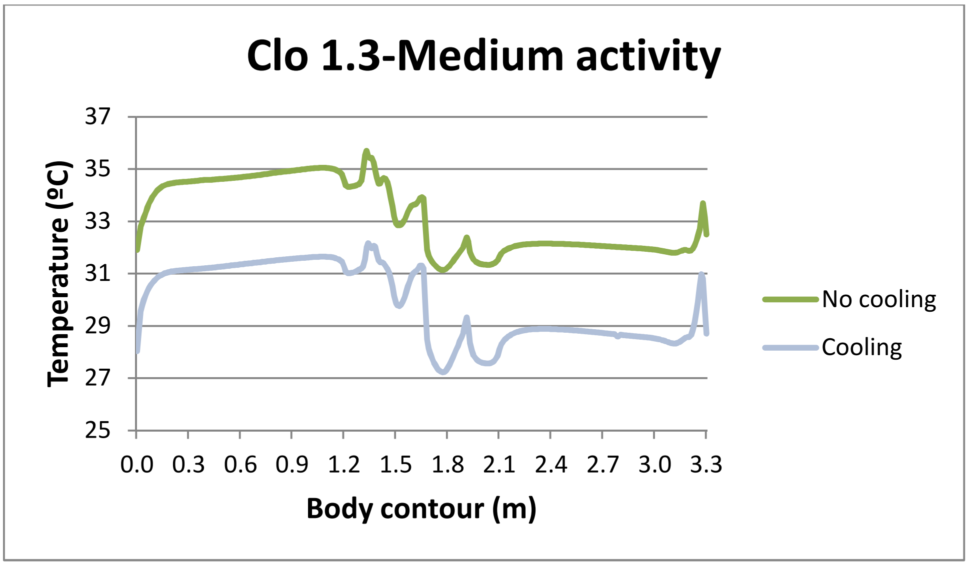

Fig 5.60 Clothing temperature in cases with 1.3 clo and medium activity (ºC)

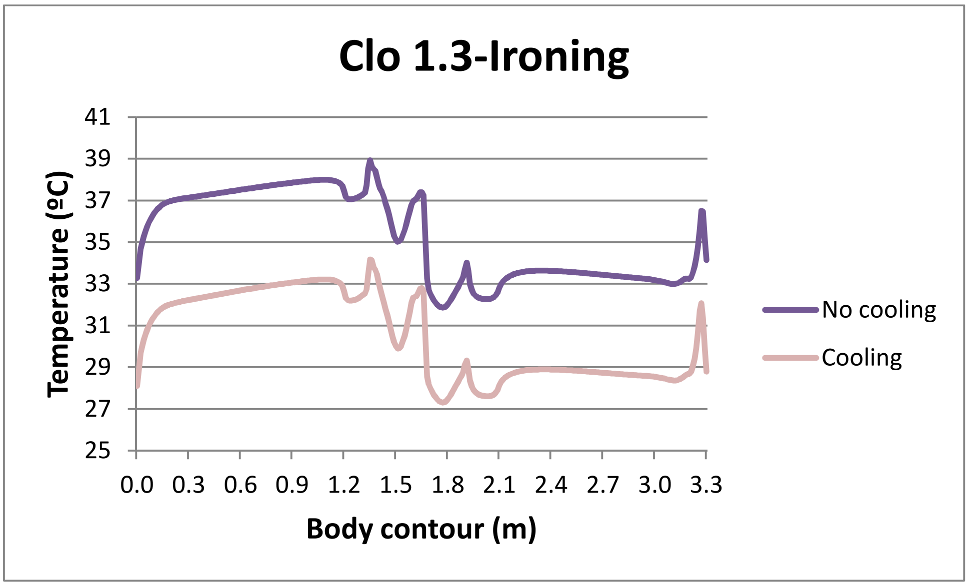

Fig 5.61 Clothing temperature in cases with 1.3 clo and ironing (ºC)

5.9 TEMPERATURE OF THE SKIN. COOLING VS NO COOLING

In this section I'm going to analyze the skin temperature in the cooling and no cooling cases with the same value of activity and clothing in order to show what the differences among both situations are.

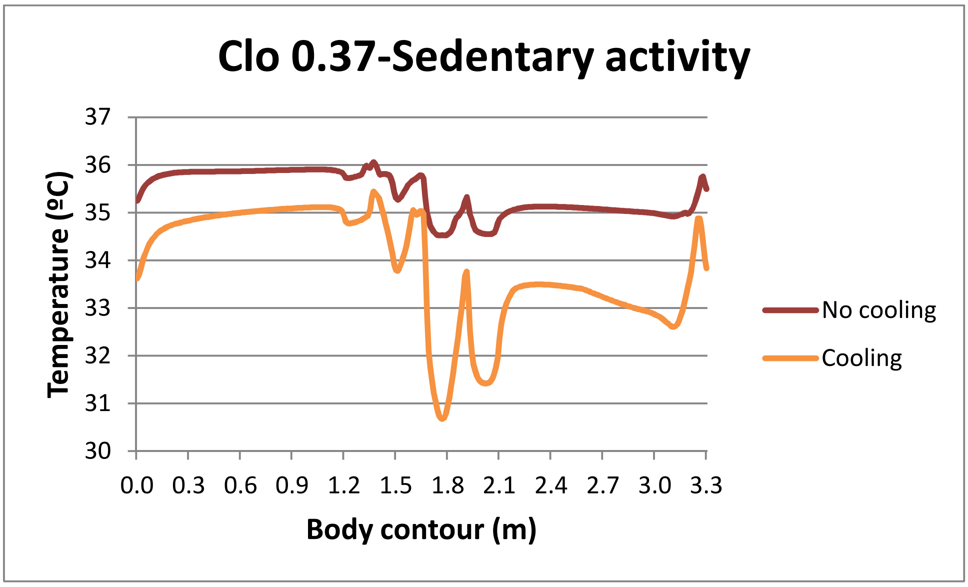

Fig 5.62 Skin temperature in cases with 0.37 clo and sedentary activity (ºC)

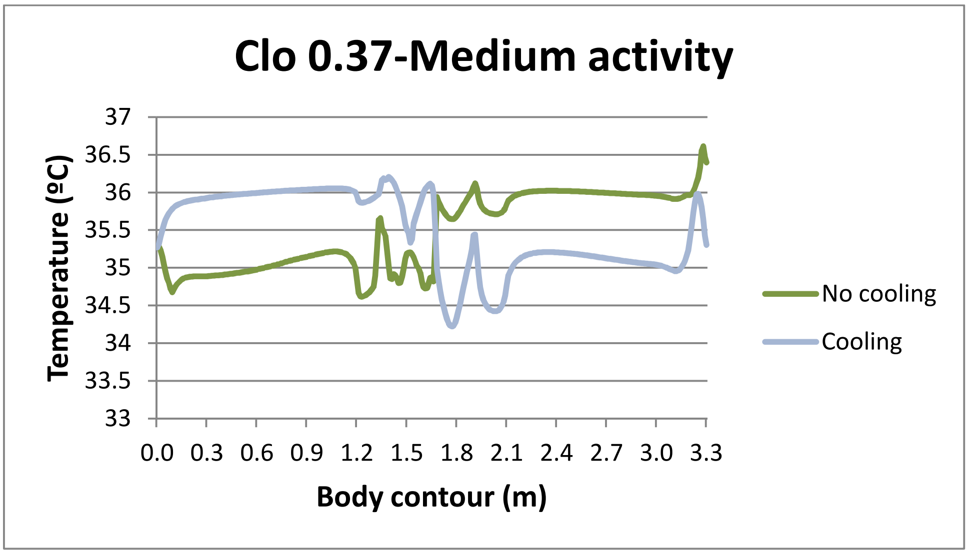

Fig 5.63 Skin temperature in cases with 0.37 clo and medium activity (ºC)

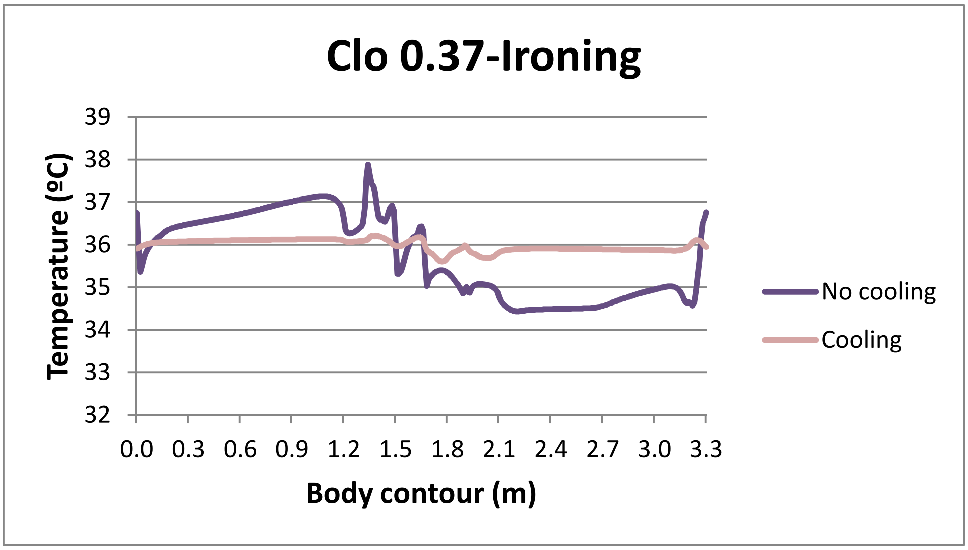

Fig 5.64 Skin temperature in cases with 0.37 clo and ironing (ºC)

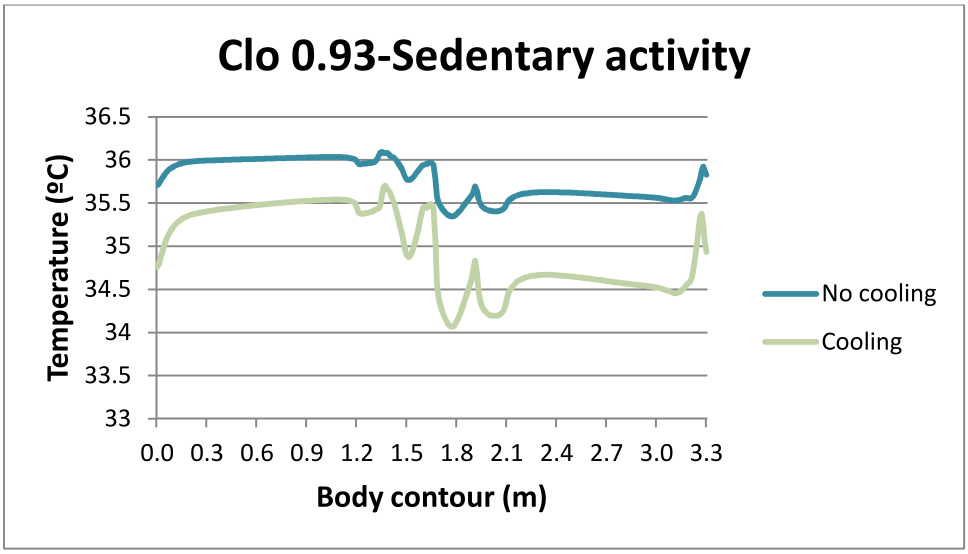

Fig 5.65 Skin temperature in cases with 0.93 clo and sedentary activity (ºC)

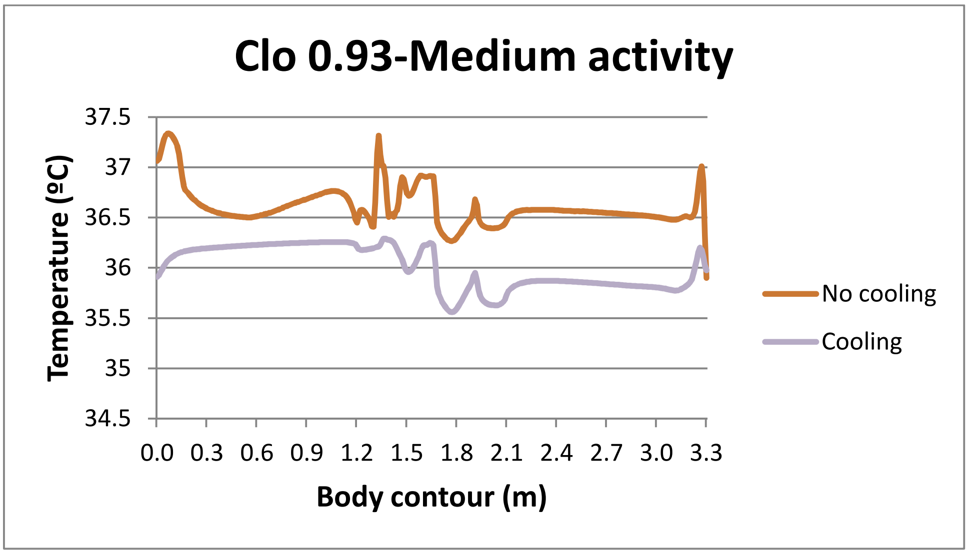

Fig 5.66 Skin temperature in cases with 0.93 clo and medium activity (ºC)

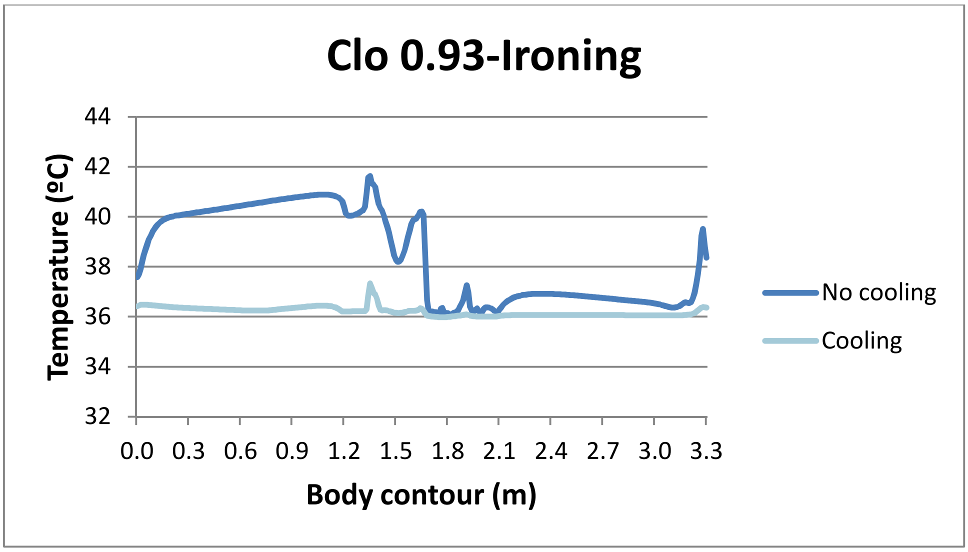

Fig 5.67 Skin temperature in cases with 0.93 clo and ironing (ºC)

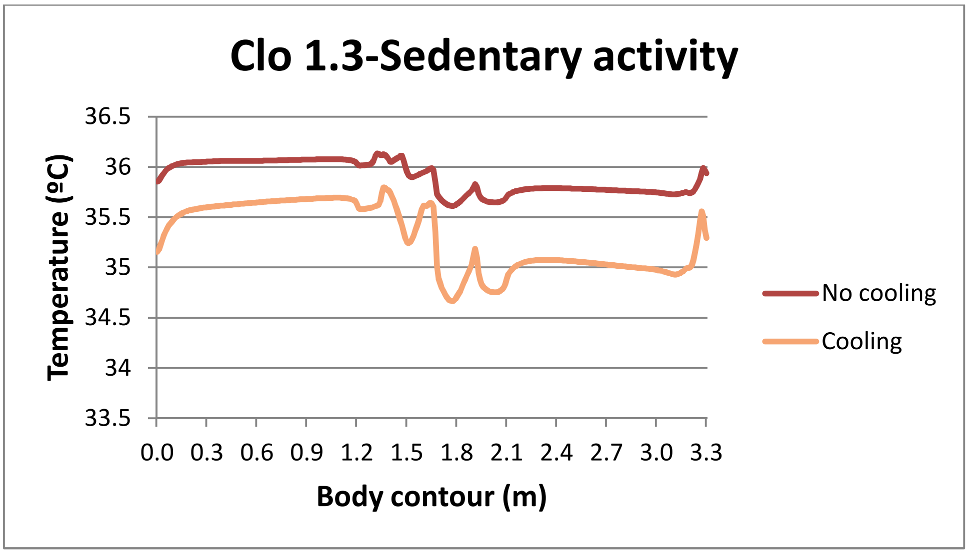

Fig 5.68 Skin temperature in cases with 1.3 clo and sedentary activity (ºC)

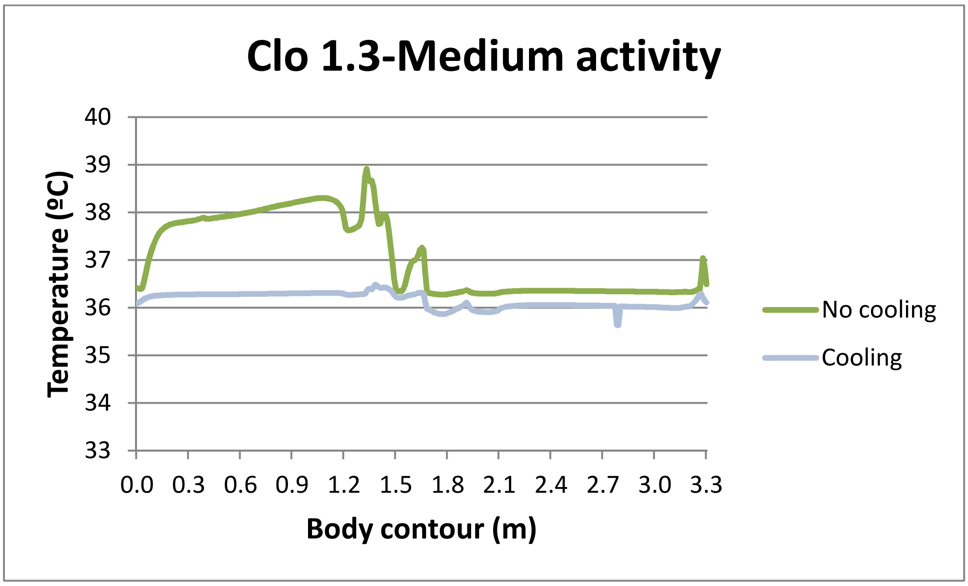

Fig 5.69 Skin temperature in cases with 1.3 clo and medium activity (ºC)

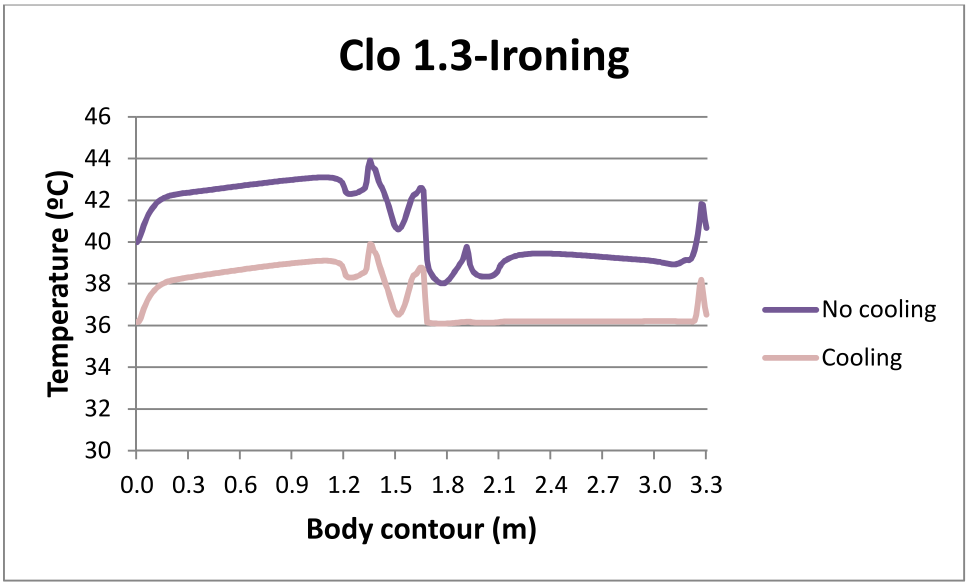

Fig 5.70 Skin temperature in cases with 1.3 clo and ironing (ºC)

As can we seeing in this set of graphics the tendency and the shape of the cases with the same clothing and the same activity is more or less similar.

There are a difference among the cases in a cooling situation and the cases without cooling. In almost all the pictures the case which are in the no cooling situation are above of the cooling case, because the air temperature is higher, it has a value of 28ºC and the heat transfer between the body and the surroundings is lower due to the smaller temperature difference and in consequence the heat transfer by convection drops and the temperature in the skin and in the clothes surface rises.

5.10 HEAT FLUX COMPARISONS

5.10.1 Heat flux according to the clothing. Cooling case

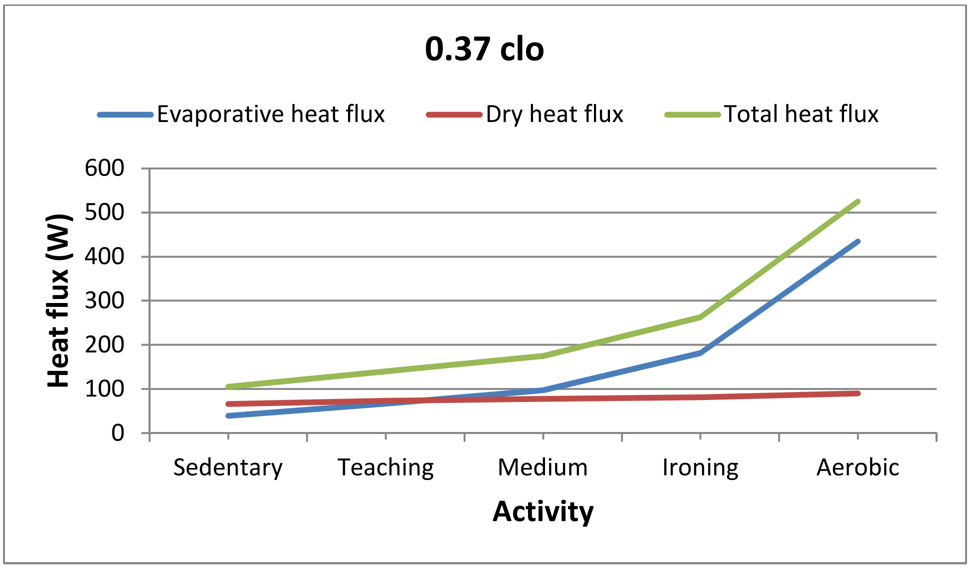

Fig 5.71 Heat fluxes in cases with 0.37 clo (W)

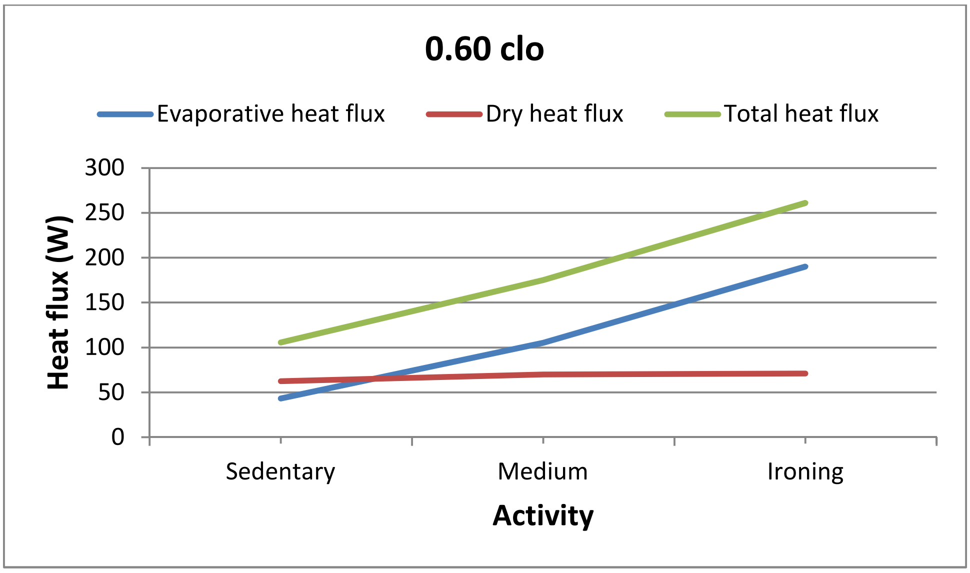

Fig 5.72 Heat fluxes in cases with 0.60 clo (W)

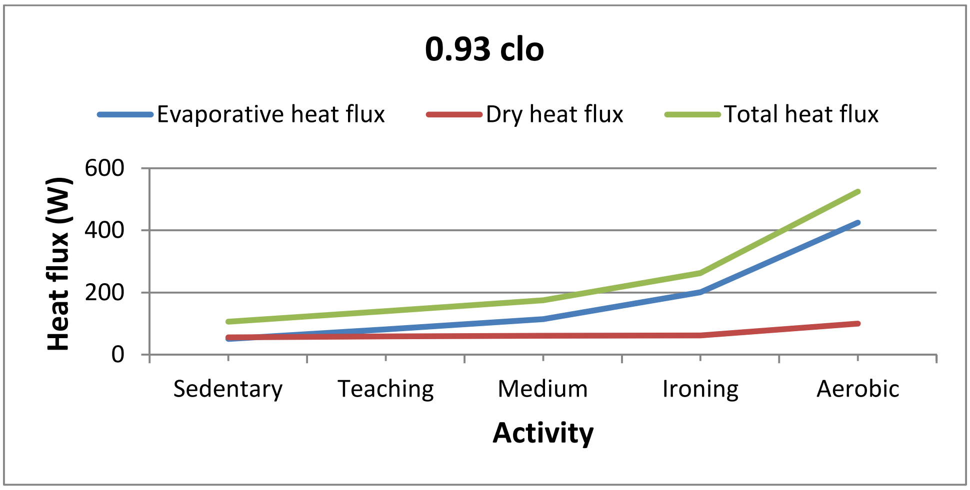

Fig 5.73 Heat fluxes in cases with 0.93 clo (W)

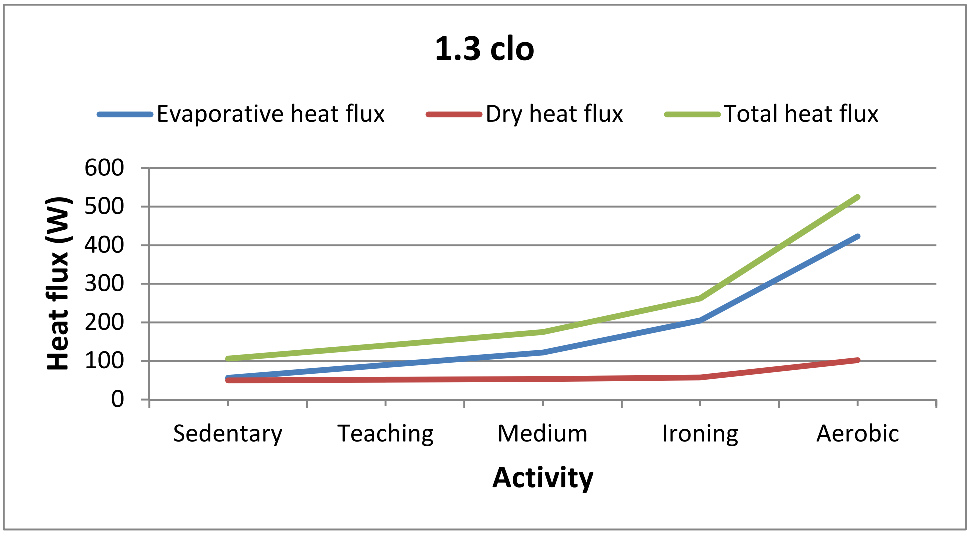

Fig 5.74 Heat fluxes in cases with 1.3 clo (W)

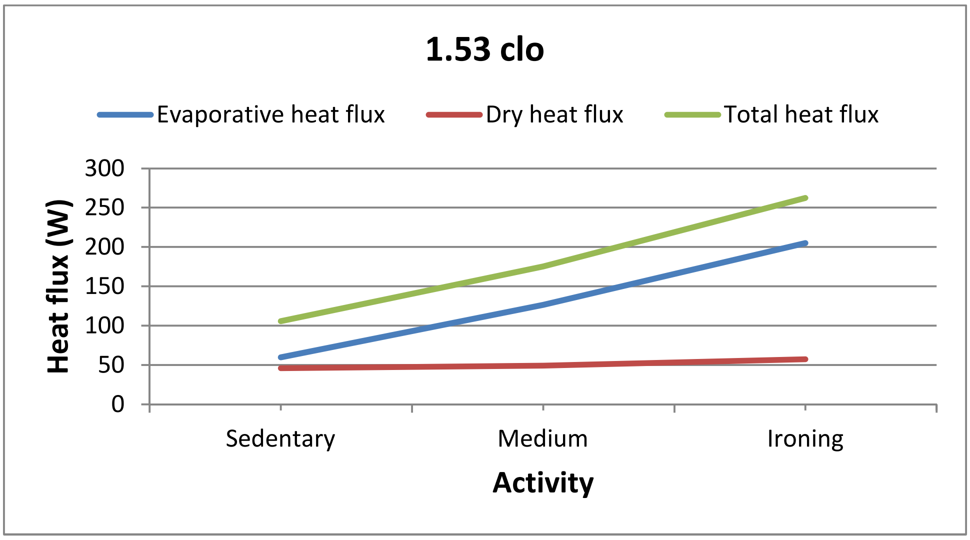

Fig 5.75 Heat fluxes in cases with 1.53 clo (W)

As we can see in this collection of graphics the influence of the heat lost by evaporation of the sweat is increasing as higher is the activity that we are doing. For activities not very strong the evacuated heat by evaporation is alike or even lower than the evacuated heat by convection reaching the maximum difference when the activity is aerobic (6 met = 592 W). This is because when the physical exercise rises the metabolic heat also increases so it needs to evacuate more heat with the sweat evaporation not to collapse the organism with a high temperature because as we can see the evacuated heat by convection (dry heat flux) is more or less constant during all the graphic and suffers a little variation as higher is the value of the activity and the clothing due to the environmental conditions (air velocity, air temperature…) are constant.

The value of the evacuated heat is in all the graphics around 50 W but the evaporative heat flux is between 50 W with sedentary activity and more than 400 W doing aerobic. Therefore the total heat flux in these cases are among 100 and 500 W.

5.10.2 Heat flux according to the clothing. No Cooling case

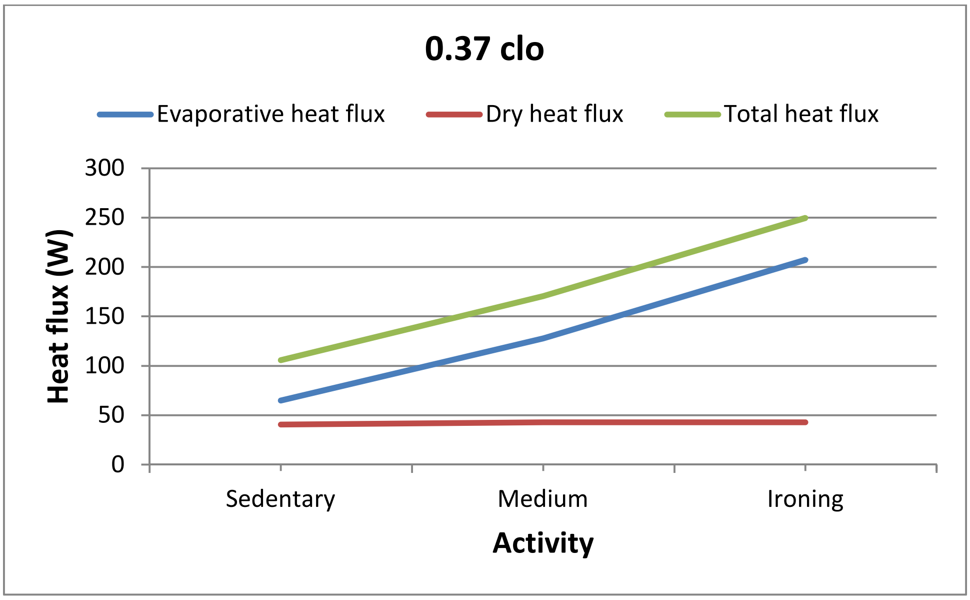

Fig 5.76 Heat fluxes in cases with 0.37 clo (W)

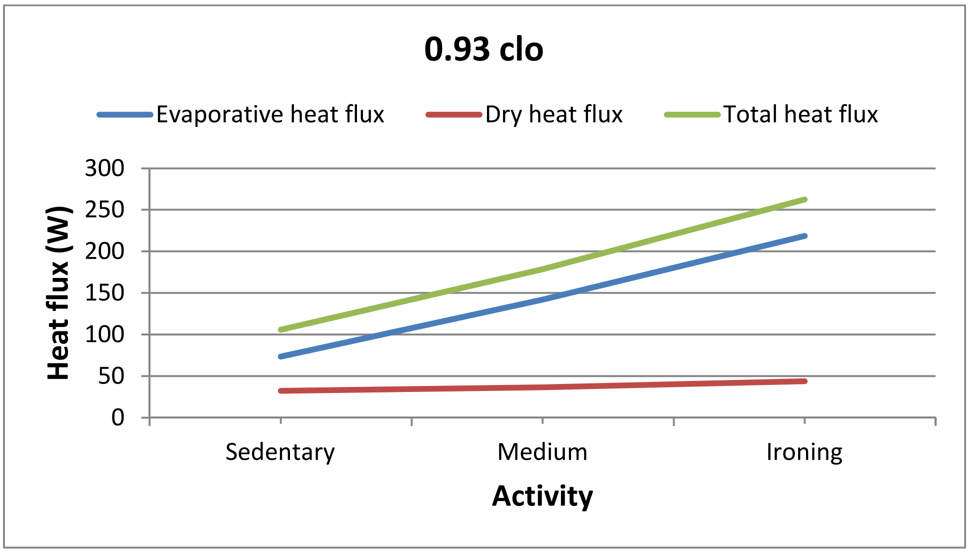

Fig 5.77 Heat fluxes in cases with 0.93 clo (W)

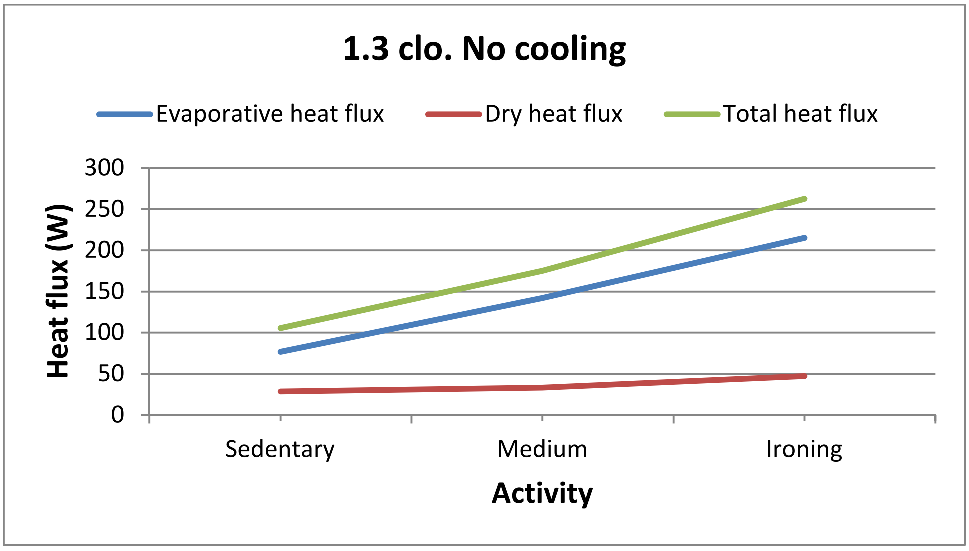

Fig 5.78 Heat fluxes in cases with 1.3 clo (W)

Respecting to the cases without cooling I can say that one of the differences respect of the previous cases is that the evaporative heat flux is always above the dry heat flux even when you are doing a sedentary activity so it has more more influence or is more important when you are evacuating the heat .This is due to the increase of the air temperature which produces that the heat transfer by convection decreases because the temperature difference among the skin or the clothing surface and the air of the surroundings is lower than in the previous cases. This causes that the person should sweat more (the evaporative heat flux rises) in order to evacuate this metabolic heat.

Here the values of the dry heat flux are between 25 with a sedentary activity and less than 50 W ironing (3 met=296 W).The evaporative heat flux rises from 75 W to 220 W, so the total heat evacuated by the human body in this environmental conditions is among 100 and 220 W which is less than the metabolic heat produced (119 W for sedentary activity and 296 W for ironing) because I haven't taken into consideration the radiation and breathing losses.

5.10.3 Heat flux according to the activity. Cooling case

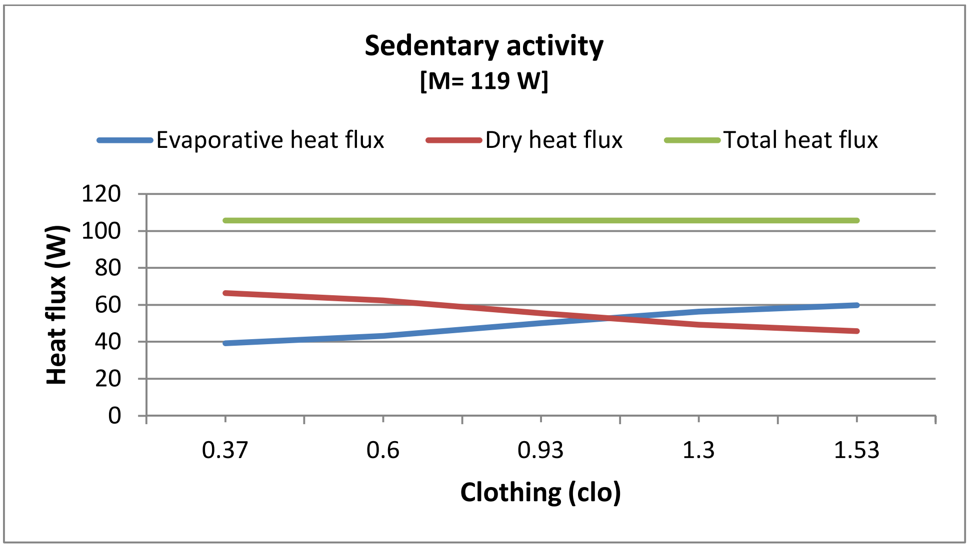

Fig 5.79 Heat fluxes in sedentary activity cases (W)

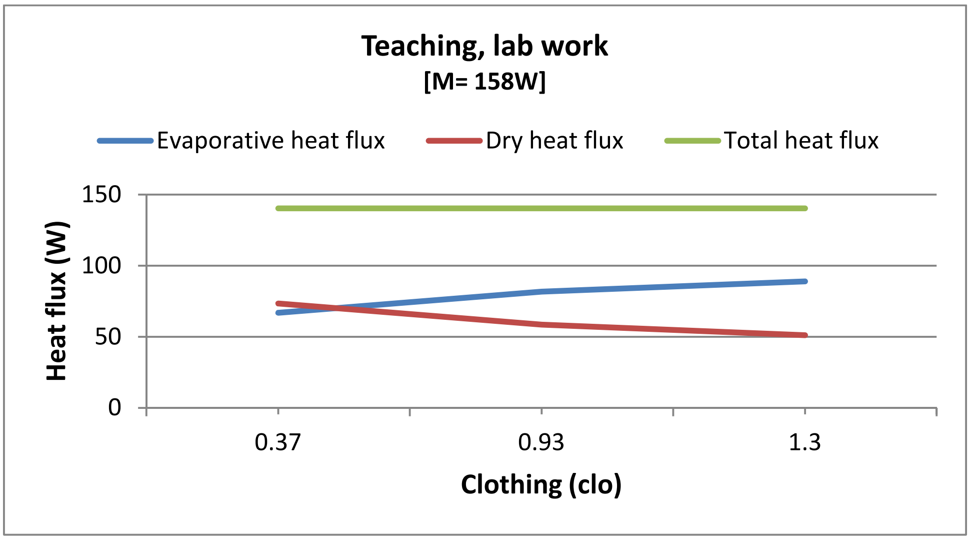

Fig 5.80 Heat fluxes in teaching, lab work cases (W)

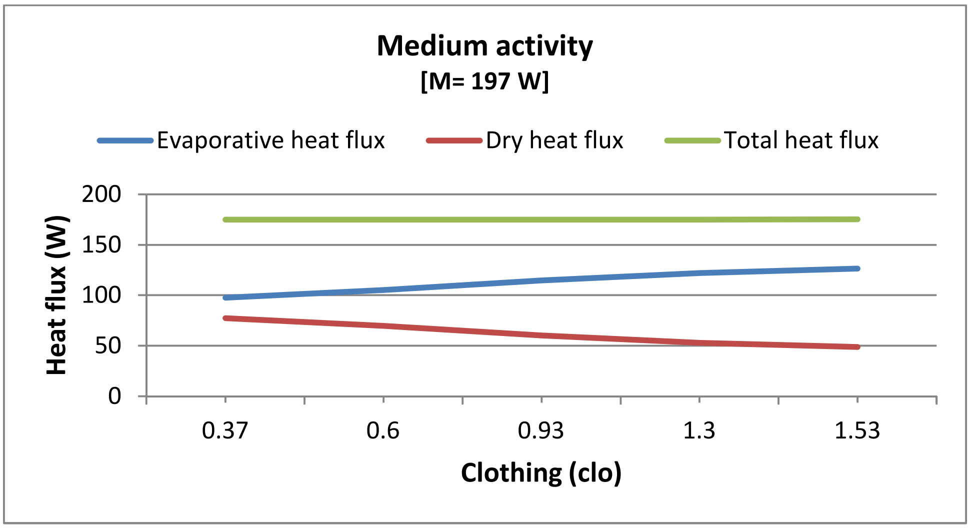

Fig 5.81 Heat fluxes in medium activity cases (W)

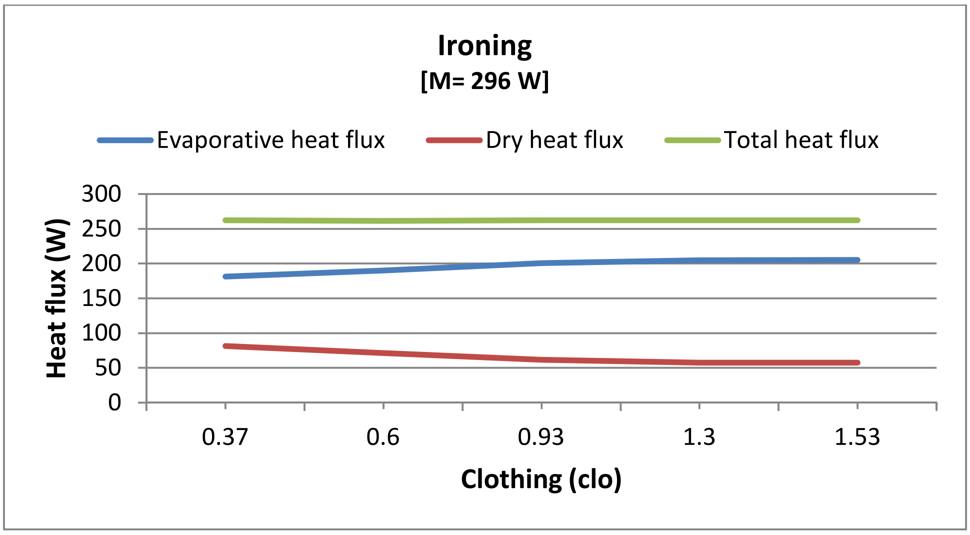

Fig 5.82 Heat fluxes in ironing cases (W)

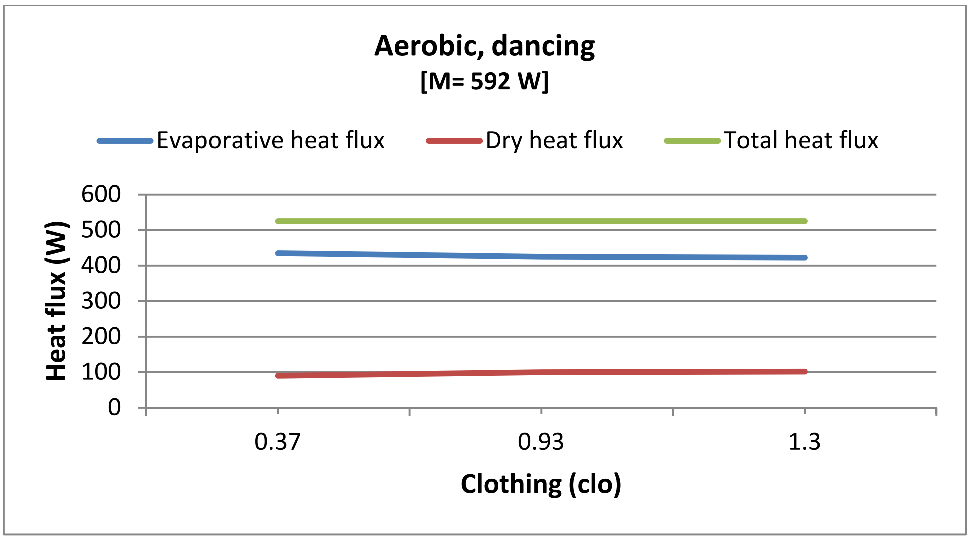

Fig 5.83 Heat fluxes in aerobic, dancing cases (W)

In these graphics we can see again hw the value of the evaporative heat flux increases with the activity. But the most representative characteristic is that in all the graphics the evaporative heat flux rises as you are wearing a bigger layer of clothes but otherwise the dry heat flux decreases as the clothing increases.
Also as higher is the activity lower is the rise or the drop of these two variables, and with the aerobic activity the lines are almost horizontal (constant) in both case. This is caused because when you dress more clothes is more difficult to transfer the heat to the environment due to the body is more isolated so the effect of the convection is lower but on the other hand you sweat more so you can evacuate more evaporative heat as we can see with all the activities.
The values of the evaporative heat flux are between 40 and 450 W and the dry heat flux values are among 50 and 100 W for the aerobic activity with 1.3 clo.
The total heat flux evacuated is between 100 and 550 W

5.10.4 Heat flux according to the activity. No Cooling case

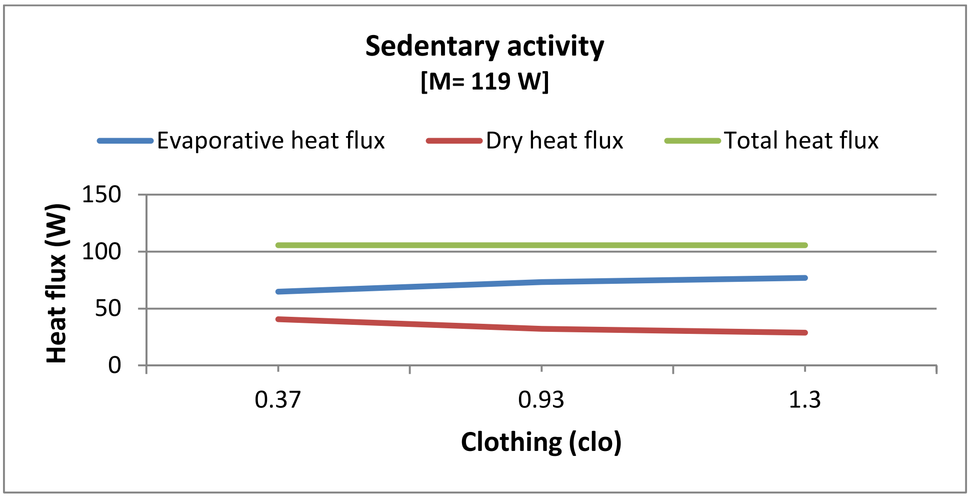

Fig 5.84 Heat fluxes in sedentary activity cases (W)

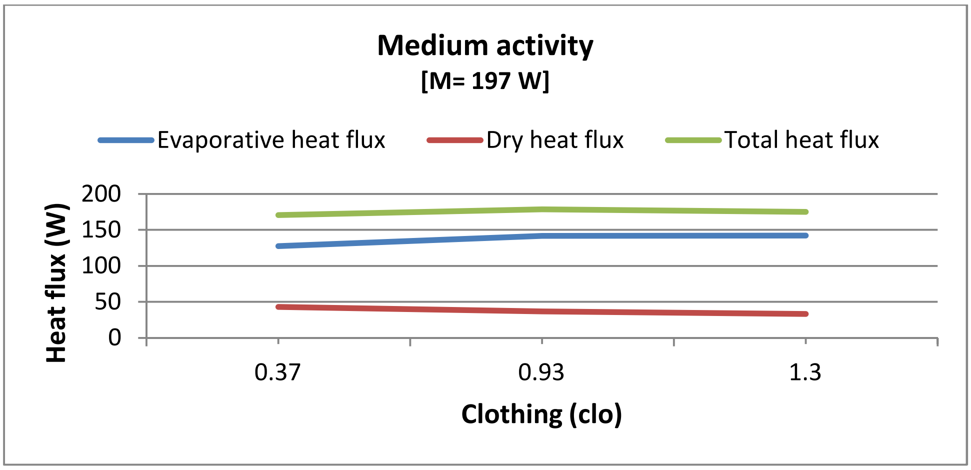

Fig 5.85 Heat fluxes in medium activity cases (W)

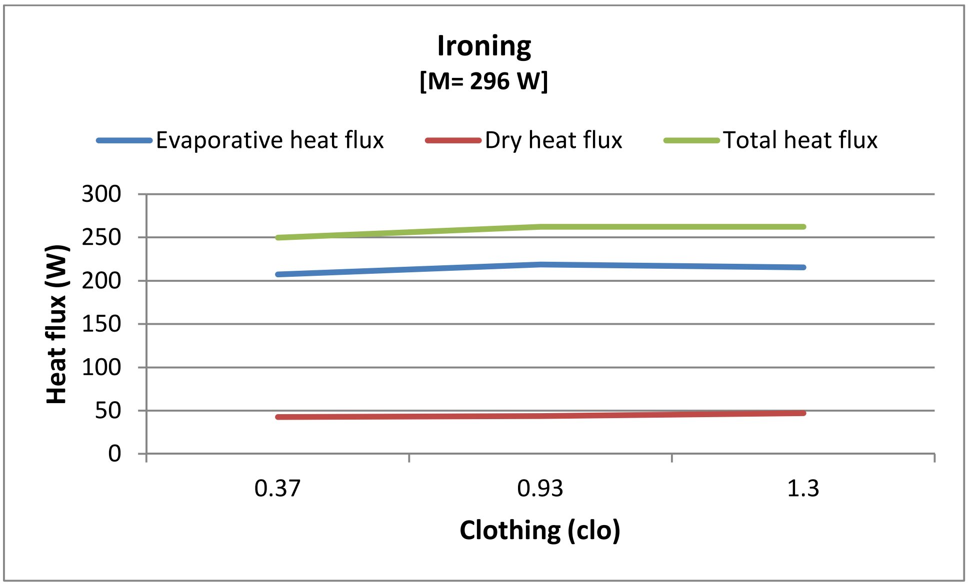

Fig 5.86 Heat fluxes in ironing cases (W)

In this case we can see how the evaporative heat flux is higher than the dry heat flux for all kinds of clothing and the difference among both is bigger each time, for example for the sedentary activity is around 40 W and for activities with high met the difference is almost 200 W.

Also I want to show that the values for the evaporative heat flux are higher than the values in the case with the same activity but cooling, and however the dry heat flux is lower in the no cooling cases as happen in section 5.10.2

Here the values for the 3 activities are quite uniform because we have lines almost horizontal, therefore the increase of the amount of clothes doesn't have influence in the evacuation of the heat when we are in a room with a high air temperature.

On the other hand the values for the dry heat flux are around 30-40 W and for the evaporative heat flux are between 60 and 220 W. So the total heat flux is among 100 and 250 W which is less than in the cases with cooling.

6. CONCLUSION

After analyzing the different results we can consider that there is a notable difference among the temperature reaches by the skin and the clothes. The model works rightly and the skin values are higher than in the clothes surface, because the skin is in direct contact with the metabolic heat produced by the body and is easier to raise the temperature, however all kind of clothes have an insulation coefficient which avoid the heat transfer and because of this the temperature in the clothes is lower. Beside from the point of view of the heat balance of the human body as higher is the insulation (for the same activity) higher is the difference between both parameters, which shows the influence of the clothing that we are dressing.
On the other hand each kind of activity goes associated to a way of dressing which depends of each person and that is where it comes into play the psychological, and the thermophysiological factors that make you feel comfortable or not in a particular conditions. This explain for example because one summer day there are people who feel comfortable dressing long trousers and others with short trousers although the environmental conditions are the same for all of them.

Moreover we have seen that the influence of the physical exercise we are doing is also very important because as much activity higher is the metabolic heat quantity produced and therefore the body needs to use more physiological mechanisms to evacuate the heat. The heat flux is clearly higher when the activity increases because the internal organs of the human body are working with a higher rhythm than when a person is at rest.
In fact is very important to know what the weather conditions are because depending of this you can think about doing one activity or other. In particular conditions there are activities that can be dangerous or unhealthy because the body comes collapsed, such as doing activities with high met value during days with high temperatures.
Therefore the activity and the way of dressing are inhently related because each kind of clothing must be used for a particular activity as we have seen in this project.I have analyzed cases that are not realistic because not only have high met (aerobic), but also have high clothing insulation (winter clo of 1.3 clo!). This setup (high met & clo) may not be possible in reality in a steady state. When the body undergoes such a stress for a long time, the increased body temperature will exhaust the body mechanisms to cool, and the activity level will drop (that is,, person will not be able to maintain that activity, the muscles will refuse to work at temperatures when the proteins start to disintegrate 42-43 ºC). So in reality the Met will drop, but the model is steady state and fails to acknowledge that, so it produces clear nonsense inside the body, but

reasonable heat and moisture fluxes on the body surface. So, at such extremes, the parameters inside the body aren't believable.
The influence of treating the cases with cooling and without cooling is clear because the air temperature is one of the most important elements. Affects to the exchanged heat flux and feeling more comfortable is more difficult when you are during summer in a place without air conditioning, because all the elements (walls, tables, windows) which are in the room increases their temperature and they give off more hot.The solution in this case is complex because drop the temperature without mechanical help (air conditioning) in a lot of places in impossible because of the weather and besides when you feel hot you can take off clothes but this has a limit because to a greater or lesser degree you have to be dressed.
Therefore we can consider that in some places, countries or cities the use of air conditioning is necessary to feel comfortable.

On the other hand, I think that another important factor in this project is the layout of the elements that have taken part in the analysis because having the air supply entrance in the top-left and the air outlet in the bottom-right generate that the right part of the dummy is more affected by the air flow and this has influence for example in the cooling by convection and evaporation.

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TABLE OF FIGURES

APPENDICE

A.CODES

A.1. VISUAL BASIC CODE (C++)

This file contains the calculations

```
#include "udf.h"
#include "Stdlib.h"
#include "Math.h"
#include "mem.h"


#define LR      16.5e-3    /* Luis number, [K/Pa] */

/* human physiological data */
#define tcrn    36.8  /* core temperature at neutrality, [deg.C]
*/
#define tskn    33.7  /* skin temperature at neutrality, [deg.C]
*/

/* thermodynamic constants */
#define K       5.28  /* overall heat conductance between core
and skin layer, [W/m2K] */
#define cpbl    4.187e3    /* heat capacity of blood, [J/kg.K]
*/
#define hfg          2.430e6    /* latent heat of evaporation of
water at 30 deg.C, [J/kg] */

/* ambient atmospheric conditions */
#define ta      25         /* ambient air temperature to be used
for calculation of Cres, [deg. C] */
#define pa      1500  /* ambient vapor pressure to be used for
calculation of Eres, [Pa] */

/* Clothing data */
#define Rcl          0.0945          /* thermal resistance of
clothing, [m2K/W] */
#define icl          0.41       /* vapor permeation efficeincy
of clothing, [-] */
#define fcl          1.20       /* clothing area factor, Acl/AD,
[-] */

/* metabolic heat production, [W/m2] */
#define M       70

/*  UDM 0 - Esk
     UDM 1 - w
     UDM 2 - tsk
     UDM 3 - tcr
     UDM 4 - mbl */
```

```
real  Esk,w,tcr,tsk,tcl,
           Cres=0.0014*M*(34-ta),Eres=1.72e-5*M*(5867-pa); /*
dry and latent respiration heat loss */
Thread     *t0;
FILE *fp;    /*  define a local pointer fp of type FILE  */


DEFINE_EXECUTE_ON_LOADING(file_open,libname)
{
      fp = fopen("dump.txt","w");
}

DEFINE_ON_DEMAND(file_close)
{
      fclose(fp);
}


DEFINE_DIFFUSIVITY(moisture_diff,c,t,i)
{
     return 2.88e-5 + C_MU_T(c,t) / 0.7;
}

DEFINE_PROFILE(dryheat,t,i)
{
      int tcr_count,area_count,
           hotwarning; /* checks weather the regulatory sweat
rate Ersw exceeds Emax */
      real
C,R,tb,tbn,mbl,alpha_e,beta,eps_tcr=0.0005,WSIGcr,CSIGsk,psks,Em
ax,WSIGb,WSIGsk,mrsw,Ersw,ftcr,hc,A[ND_ND],area,ds,es,A_by_es,dr
0,
           flp, /* function at the left boundary, used by the
bisection method to determine tcr */
           lp,rp, /* left and right interval point */
           relax=0.1; /* relaxation for the evaporative heat
loss Esk */

      face_t f;
      cell_t c0;


      t0 = THREAD_T0(t);
      begin_f_loop(f,t)
     {

           c0 = F_C0(f,t);
           tcl = F_T(f,t)-273.15;     /* get temperature of cell
adjacent to boundary */

           F_AREA(A,f,t);

           area=0;
           for (area_count=0; area_count<ND_ND; area_count++)
                area+=A[area_count]*A[area_count];
           area=sqrt(area);
```

```
          R=F_STORAGE_R(f,t,SV_RAD_HEAT_FLUX)/area;
          C=F_STORAGE_R(f,t,SV_HEAT_FLUX)/area-R;

          tsk = tcl + (C+R)*Rcl;
          tcr_count=0;
          lp=30;
          rp=40;
          flp=+1.0;

          /* calculate tcr */
               do
               {
                    tcr_count++;
                    tcr=(lp+rp)/2.0;

                    /* warm signal from body core */
                    WSIGcr=tcr-tcrn;
                    if (WSIGcr < 0) WSIGcr=0;

                    /* cold signal from body skin */
                    CSIGsk=tskn-tsk;
                    if (CSIGsk < 0) CSIGsk=0;


     mbl=((6.3+200*WSIGcr)/(1+0.5*CSIGsk))/3600;
                     if (mbl > 0.025) mbl = 0.025;
                    if (mbl < 1.4e-4) mbl = 1.4e-4;

                    ftcr=(M-Eres-Cres)/(K+cpbl*mbl)+tsk-tcr;
                    if (ftcr*flp<0)
                         rp=tcr;
                    else
                    {
                         lp=tcr;
                         flp=ftcr;
                    }
               }
               while ( rp-lp > eps_tcr );
          C_UDMI(c0,t0,2)=tsk;
          C_UDMI(c0,t0,3)=tcr;
          C_UDMI(c0,t0,4)=mbl;

          hc=C/(tcl-ta);
          alpha_e=LR/(Rcl/icl+1/(fcl*hc)); /* total evaporative
heat transfer coefficient, [W/m2Pa] */
          psks=100*exp(18.956-4030.18/(tsk+235));
          Emax=alpha_e*(psks-pa);

          beta=0.0418+0.745/(3600*mbl+0.585);   /* skin mass
fraction */
          tb=beta*tsk+(1-beta)*tcr;
          tbn=beta*tskn+(1-beta)*tcrn;

          WSIGb=tb-tbn;
          if (WSIGb<0) WSIGb=0;
```

```
            WSIGsk=tsk-tskn;
            if (WSIGsk<0) WSIGsk=0;

            /* evaporative heat loss due to sweating */
            mrsw=4.7e-5*WSIGb*exp(WSIGsk/10.7);
            Ersw=mrsw*hfg;

            hotwarning=0;
            if (Ersw>Emax)
            {
                  hotwarning=1;
                  Ersw=Emax;
            }

            /* skin wettedness */
            w=0.06+0.94*(Ersw/Emax);
            C_UDMI(c0,t0,1)=w;

            /* evaporative heat loss Esk */
            C_UDMI(c0,t0,0) += relax*(w*Emax-C_UDMI(c0,t0,0));
            F_UDMI(f,t,0)=C_UDMI(c0,t0,0);

            /* dry heat loss R+C */
            F_PROFILE(f,t,i)=M-Eres-Cres-C_UDMI(c0,t0,0);

            if (hotwarning==1) fprintf(fp,"f=%d tcl=%5.2f
tsk=%5.2f tcr=%5.2f w=%3.2f mbl=%f hc=%6.2f psks=%f Emax=%7.2f
Ersw=%7.2f Esk=%7.2f C=%7.2f R=%7.2f dryheat=%f
\n",f,tcl,tsk,tcr,w,mbl,hc,psks,Emax,Ersw,C_UDMI(c0,t0,0),C,R,M-
Eres-Cres-C_UDMI(c0,t0,0));

      }
      end_f_loop(f,t);
      fprintf(fp," \n");
}


DEFINE_PROFILE(msk,t,i)
{     face_t f;

      begin_f_loop(f,t)
      {
            F_PROFILE(f,t,i)=F_UDMI(f,t,0)/hfg;  /* moisture
generated from skin, [kg/s.m2] */
      }
      end_f_loop(f,t);

}
```

A.2. CODE CHANGES

In this table I show the code changes that I have done in the value of different parameters in order to reach convergence in the calculus and in consequence obtain good results:

CASE	RELAX	lp	rp
1	0.04	10	60
2	0.04	10	60
5	0.04	10	60
6	0.04	10	60
9	0.02	0	100
10	0.04	10	60
11	0.04	10	60
12	0.04	10	60
14	0.02	0	100
15	0.04	10	60
18	0.04	10	60
19	0.03	20	60
20	0.04	10	60
22	0.04	10	60
25	0.1	20	60
28	0.04	10	60
29	0.04	10	60

Note: The value of 0.04 for the relax parameter is bit low if you are looking for accuracy, because the simulation may converge before the correct properties inside the body are achieved. For this purpose, I have set stricter convergence criteria in fluent in order to do more iterations and let the body to reach the correct conditions.